BEFORE THE ILLINOIS POLLUTION CONTROL BOARD

ILLINOIS POWER GENERATING COMPANY,	)	
Petitioner,	)	
v.	)	**PCB 2024-043**
ILLINOIS ENVIRONMENTAL PROTECTION AGENCY,	)	
Respondent.	)	

NOTICE OF FILING

To: See Attached Service List (Via Electronic Filing)

PLEASE TAKE NOTICE that the undersigned filed today with the Office of the Clerk of the Illinois Pollution Control Board by electronic filing the following NOTICE OF FILING, CERTIFICATE OF SERVICE, CERTIFICATE OF RECORD ON APPEAL, and RECORD ON APPEAL (consisting of 21 parts), a copy of which is attached hereto and hereby served upon you.

Respectfully submitted,

ILLINOIS ENVIRONMENTAL PROTECTION AGENCY

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CERTIFICATE OF SERVICE

I hereby certify that I did on March 26, 2024, prior to 5:00 PM, cause to be served by electronic mail, a true and correct copy of the following instruments entitled NOTICE OF FILING, CERTIFICATE OF SERVICE, CERTIFICATE OF RECORD ON APPEAL, and RECORD (consisting of 21 parts), consisting of 2,222 pages in total, to:

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Under penalties as provided by law pursuant to Section 1-109 of the Code of Civil Procedure, the undersigned certifies that the statements set forth in this Certificate of Service are true and correct, except as to matters therein stated to be on information and belief and as to such matters the undersigned certifies as aforesaid that he verily believes the same to be true.

s/Samuel Henderson
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Assistant Attorney General
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BEFORE THE ILLINOIS POLLUTION CONTROL BOARD

ILLINOIS POWER)
GENERATING COMPANY,)
)
Petitioner,)
)
v.) **PCB 2024-043**
) **(Alternative Source Demonstration**
) **– Petition for Review)**
ILLINOIS ENVIRONMENTAL)
PROTECTION AGENCY,)
)
Respondent.)

CERTIFICATE OF RECORD ON APPEAL

Respondent, ILLINOIS ENVIRONMENTAL PROTECTION AGENCY ("Illinois EPA"), in accordance with the procedural rules of the Illinois Pollution Control Board ("Illinois PCB") as set forth in 35 Ill. Adm. Code 105.212 and 105.116, files as its Record in this cause the Illinois EPA's record of non-concurrence with the Newton Primary Ash Pond Alternative Source Demonstration ("ASD") which is attached and consists of the following documents:

PAGES	**DOCUMENT**		**DATE**
R000002 - R000011	1	Drever, James I. The Geochemistry of Natural Waters: Surface and Groundwater Environments. Prentice Hall. Third Edition.	1997
R000013 - R000022	2	Faybishenko, Boris, Paul A. Witherspoon and Sally M. Benson Editors. Dynamics of Fluids in Fractured Rock. American Geophysical Union.	2000
R000024 - R000031	3	Eby, G. Nelson. Principles of Environmental Geochemistry. Brooks/Cole, Cengage Learning.	2004
R000033 - R000062	4	United States Environmental Protection Agency (USEPA). SW-846 Test Method 1314: Liquid-Solid Partitioning as a Function of Liquid-Solid Ratio for Constituents in Solid Materials Using An Up-Flow Percolation Column Procedure.	July, 2017

PAGES	DOCUMENT		DATE
R000064 - R000100	5	United States Environmental Protection Agency (USEPA). SW-846 Test Method 1315: Mass Transfer Rates of Constituents in Monolithic or Compacted Granular Materials Using a Semi-Dynamic Tank Leaching Procedure.	July, 2017
R000102 - R000121	6	SW-846 Test Method 1316: Liquid-Solid Partitioning as a Function of Liquid-to-Solid Ratio in Solid Materials Using a Parallel Batch Procedure.	July, 2017
R000123 - R000152	7	United States Environmental Protection Agency (USEPA) Region I. Low Stress (Low Flow) Purging And Sampling Procedure For The Collection Of Groundwater Samples From Monitoring Wells.	September 19, 2017
R000154 - R000421	8	Fetter, C.W., Thomas Boving, and David Kreamer. Contaminant Hydrogeology. Waveland Press. Third Edition.	2018
R000422 - R000562	9	Illinois Pollution Control Board (IPCB). Standards for the Disposal of Coal Combustion Residuals in Surface Impoundments; 35 Illinois Administrative Code Part 845.	April 21, 2021
R000564 - R001588	10	Copy of Illinois Power Generating Company's Operating Permit Application for the Newton Power Plant Primary Ash Pond and submittal letter	October 25, 2021
R001560 - R001604	11	United States Environmental Protection Agency (USEPA). Pore Water Sampling. USEPA Publication No. LSASDPROC-513-R5.	April 22, 2023
R001606 - R001639	12	2023 Quarter 2 Ash Pond Alternative Source Demonstration (ASD)	October 6, 2023
R001641	13	Email from Joshua Seif titled "2023 Qtr. 2 ASD Exceedance letter - Newton Primary Ash Pond - #W0798070001-01"	October 11, 2023
R001643 - R001646	14	Email chain with top email from Lynn Dunaway titled "FW: Face to Face Meeting Request" and dated October 17, 2023 1:17:54 PM	October 12-17, 2023
R001648 - R001649	15	Handwritten notes of Heather Mullenax	October 19, 2023
R001651 - R001754	16	Copy of Alternative Source Determination Submittal and Letter, Quarter 2, 2023, East Ash Pond Joppa Power Plant, Joppa Illinois [attachment to email of October 25, 2023, document 14]	October 20, 2023
R001756	17	Printout of page from Newton ASD with handwritten notes	October 24, 2023

PAGES	DOCUMENT		DATE
R001758	18	Email from EPA.CCR.Part845.Notify titled "Alternate Source Demonstration - Newton Power Plant"	October 24, 2023
R001760	19	Email from Lauren Hunt titled "ASD Discussions--Newton and Joppa"	October 25, 2023 5:21 PM
R001762 - R001763	20	Email chain with top email from Dianna Tickner titled "[External] RE: Newton and Joppa ASD Questions"	October 26, 2023 10:44 AM
R001765 - R001766	21	Email from Lauren Hunt titled "Joppa and Newton ASD data gap discussion"	October 26, 2023 1:09 PM
R001768	22	Draft letter of nonconcurrence for Joppa East Ash Pond Alternative Source Determination [attachment to email of October 25, 2023, document 14]	October 26, 2023
R001770 - R001771	23	Webex meeting invite from Lauren Hunt titled "ASD discussions with Dynegy"	October 26, 2023
R001773	24	Handwritten notes of Heather Mullenax	October 31, 2023
R001775 - R001778	25	Email chain with top email from Michael Summers titled "RE: Joppa West Adjusted Standard Recommendation Meeting follow up"	November 1, 2023 3:32 PM
R001780 - R001781	26	Email chain with top email from Stefanie Diers titled "RE: Joppa AS"	November 2, 2023 7:52 AM
R001783	27	Email from Josiah Seif titled "RE: Alternate Source Demonstration - Newton Power Plant"	November 2, 2023 4:20 PM
R001785	28	Email from Brian Voelker titled "[External] Alternate Source Demonstration - Newton Power Plant"	November 3, 2023 6:20 PM
R001787 - R001945	29	Letter from Illinois Power Generating Company titled "Re: Alternative Source Demonstration ("ASD") for Newton Power Plant Primary Ash Pond" [Attachment to email of November 3, document 24]	November 3, 2023
R001947 - R001961	30	Email from Jenny Cassel titled "[External] Environmental Groups' Comments on Joppa, Baldwin, and Newton ASDs", with attachment	November 6, 2023 1:13 PM
R001963	31	Handwritten notes of Heather Mullenax	November 6, 2023
R001965	32	Letter from Michael Summers titled "Re: Newton Power Plant Primary Ash Pond - W079807001-01 Alternative Source Demonstration Submittal"	November 7, 2023
R001967 - R002214	33	Filing by Illinois Power Generating Company with Pollution Control Board of "Petition For Review Of Illinois Environmental Protection Agency's Non-	December 15, 2023

PAGES	DOCUMENT		DATE
		Concurrence With Alternative Source Demonstration Under 35 Ill. Admin. Code Part 845 And Motion For Stay; Appearances Of Joshua More, Bina Joshi, And Samuel Rasche; And A Certificate Of Service”	

I, Lauren Hunt, of the Illinois EPA, hereby certify that the documents of the Record on Appeal filed in the above referenced matter and summarized in the above Index are complete to the best of my knowledge, information, and belief.

BY: s/Lauren Hunt
Lauren Hunt
[Environmental Protection Geologist III]
Illinois Environmental Protection Agency

Respectfully submitted,

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Attorney General of the
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MATTHEW J. DUNN, Chief
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Dated: _March 26, 2024

DOCUMENT

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by organisms (nitrogen, phosphorus, sometimes carbon, potassium, and silica), biological processes are often the dominant control in surface waters. For elements utilized in only trace amounts (e.g., Mn, Cu, Ni, Mo, and Se), uptake by organisms in open waters such as lakes probably affects dissolved concentrations significantly only in environments where concentrations are low in general. In environments where concentrations are high as, for example, in polluted waters, the amounts taken up by organisms are likely to be small compared to the amounts in solution or to the amounts removed by adsorption processes.

In terrestrial systems uptake by plants can have a major influence on both heavy metals and organic compounds. One method of water treatment is to route a contaminated water through an artificially constructed wetland—a swamp with abundant plants (e.g., Wieder, 1993). Contaminants are removed by direct plant uptake, by adsorption on solid organic matter, and by precipitation as sulfides where the environment is anaerobic. One problem with artificial wetlands is that their lifetime is generally finite (a decade or so), and then the material that makes up the wetland must be disposed of.

HAVIOR OF SPECIFIC ELEMENTS

Several specific elements are discussed here to provide an overview of their behavior and to illustrate patterns of behavior that are common to many other elements.

Copper, Zinc, Cadmium, and Lead

These elements have several features in common. The dominant species in solution is a divalent cation (free or complexed). Under oxidizing conditions, they are soluble under acid conditions and their solubilities at higher pH are limited by the solubility of a carbonate or oxide/hydroxide (Figs. 9-12 to 9-16; these and subsequent figures have been simplified by omission of some possible complexes in solution involving sulfate, sulfide species, carbonate species, and OH^-. These omissions do not significantly change the diagrams for the conditions commonly encountered in fresh waters). Under reducing conditions, in the presence of sulfur all form relatively insoluble sulfides. In the absence of sulfur, copper is insoluble as the native metal (Fig. 9-16). The others behave as they do in oxidizing environments: they are relatively soluble at low pH and insoluble as carbonates/oxides/hydroxides at high pH. Copper, zinc, and cadmium form anionic species at high pH. It is rare, however, for pH values in nature to be sufficiently high for such species to be important. The response of these elements to a change in redox conditions is determined less by redox reactions involving the elements themselves than by changes occurring in sulfur species, and in Fe and Mn oxyhydroxides, which are important substrates for adsorption.

All members of the group are complexed by natural organic matter. Some binding constants for complexing of the M^{2+} ion with humic substances are shown in Table 9-2. These constants give a general indication of the strength of interaction between the metal and dissolved organic matter. The constant for calcium is included for comparison. In general, copper is the most strongly complexed member of the group and is very commonly influenced by organic complexation. Lead is next, followed by zinc and cadmium. Complexing of zinc and cadmium by organic solutes is, generally speaking, important only where concentrations of dissolved organic carbon are relatively high.

[illegible]

Ground water

All members of the group are potentially affected by adsorption on iron and manganese oxyhydroxides (Fig. 9-17), and Cd is potentially affected by adsorption on calcite. As discussed in Chapter 5, adsorption is pH dependent. Lead adsorbs at the lowest pH, followed by Cu, Zn, and Cd. The curves shown in Fig. 9-17 illustrate the results of experiments conducted under a specific set of conditions and should not be overgeneralized.

The expected behavior of these metals in the environment can be summarized as follows: under oxidizing conditions at low pH, they are all soluble and mobile. As the pH rises, their concentrations tend to decrease, first because of adsorption (particularly for Pb and Cu), and then because of the limited solubility of carbonates and oxides/hydroxides. Under reducing conditions, if sulfur is present, all should be immobilized as sulfides. If sulfur is absent, for Zn, Cd, and Pb the solubility control will be the same as under oxidizing conditions; Cu should be insoluble at all pH values. Adsorption is generally less important under reducing conditions because the most important substrates for adsorption, Fe and Mn oxyhydroxides, tend themselves to dissolve.

Arsenic and Selenium

Arsenic and selenium differ strongly from the previous examples in that both elements undergo important changes in oxidation state themselves, and both occur in solution as anions or as neutral species rather than as cations. *pe*-pH diagrams are shown in Figs. 9-18 and 9-19. Under oxidizing conditions, the dominant form of arsenic is the +V oxidation state, which is present as arsenic acid and its anions (arsenate), corresponding closely to phosphoric acid and phosphate species. For selenium, the dominant form under oxidizing conditions is selenate, which is closely analogous to sulfate. As conditions become reducing, As(V) is reduced to As(III)—arsenious acid and arsenite anions. When sulfate reduction occurs, As precipitates as a sulfide; if sulfur is absent, it remains in solution as arsenious acid or an arsenite. Elemental arsenic should be a stable species under highly reducing conditions, but it does not occur commonly in nature. For selenium, selenite species (analogous to sulfite) occur at intermediate redox levels, followed by elemental selenium and hydrogen selenide (analogous to hydrogen sulfide) species under strongly reducing conditions. Both

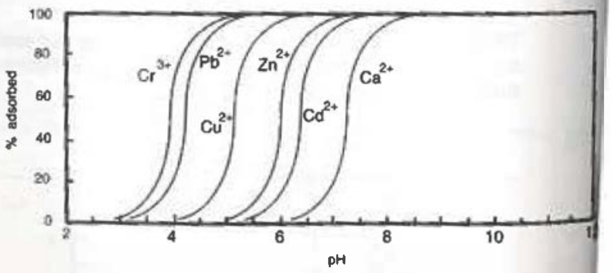


FIGURE 9-17 Adsorption of Cu^{2+}, Cd^{2+}, Zn^{2+}, Pb^{2+}, Cr^{3+}, and Ca^{2+} (for comparison) on hydrous ferric oxide as a function of pH. Each metal shows an adsorption "edge"; at pH values below the edge, the ion is not adsorbed or very weakly adsorbed. At pH values above the edge, the ion is strongly adsorbed. Conditions correspond to a high ratio of hydrous ferric oxide to adsorbing cation and an ionic strength of 0.1 m. The edges move towards higher pH as the ratio adsorbing cation:hydrous ferric oxide increases. From data in Dzombak and Morel (1990).

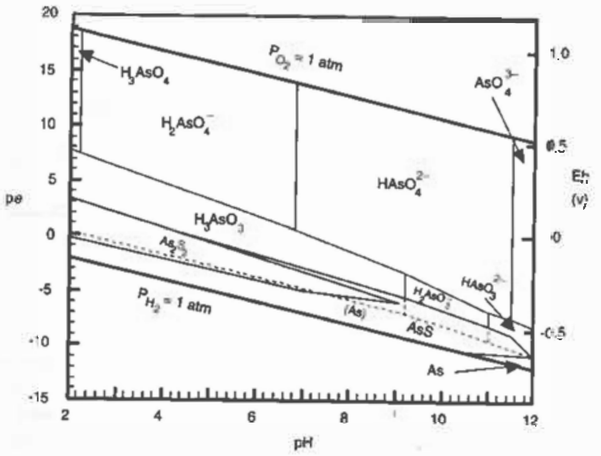


FIGURE 9-18 Simplified pe–pH diagram for the system As–O–H_2O at 25°C and one atm. Total activity of sulfur species = 10^{-2}. Light lines are boundaries involving dissolved species only. Dashed line is field of solid elemental arsenic in the absence of sulfur. Solubility is defined as a dissolved As species activity of 10^{-6}.

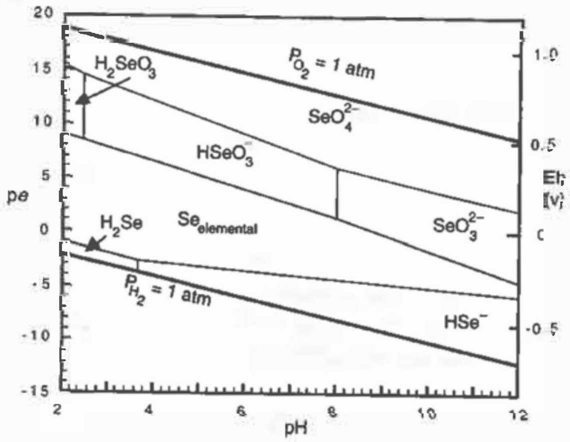


FIGURE 9-19 Simplified pe–pH diagram for the system Se–O–H_2O at 25°C and one atmosphere. Solubility is defined as a dissolved Se activity of 10^{-6}. Data are from Cowan (1988).

arsenic and selenium may be incorporated into iron sulfides under reducing conditions. The kinetics of redox transformations involving arsenic and selenium are slow, so disequilibrium is common (Kent et al., 1994; Runnells and Lindberg, 1990).

Arsenate species form inner-sphere complexes at the iron oxyhydroxide surface and are strongly adsorbed at near-neutral pH (Fig. 9-20). At high pH the strong negative charge on the oxide surface decreases adsorption of anions. As(III) apparently does not form inner-sphere complexes at the oxide surface. It is not strongly adsorbed at any pH value. For selenium, the adsorption picture is reversed. The oxidized form is only weakly adsorbed (similar to sulfate), whereas Se(IV) is strongly adsorbed under near-neutral conditions.

Organoarsenic compounds occur in nature but do not appear to be particularly important in the overall cycle of arsenic. Organic forms of selenium are more important, particularly in plants that accumulate selenium. Certain plants, notably vetches of the genus *Astragalus*, can accumulate high concentrations of selenium and may cause toxicity problems for livestock.

[illegible]

Ground Water

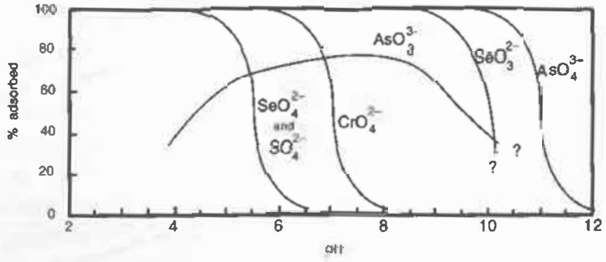
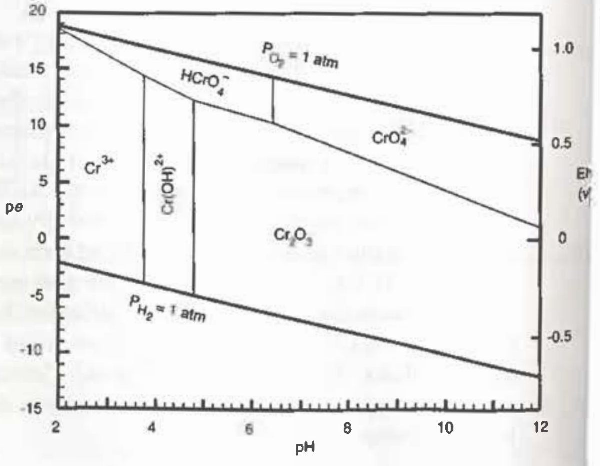


FIGURE 9-20 Adsorption of arsenate, arsenite, selenate, selenite, chromate, and sulfate (for comparison) on hydrous ferric oxide as a function of pH. Most of the anions show an adsorption "edge"; at pH values above the edge (for anions), the ion is not adsorbed or very weakly adsorbed. At pH values below the edge, the ion is strongly adsorbed. The anomalous behavior of arsenite is related to the fact that AsO_3^{3-} is fully protonated to H_3AsO_3 below pH 9 (Fig. 9-18); the symbol AsO_3^{3-} is used for all As in the +III oxidation state. Conditions correspond to a high ratio of hydrous ferric oxide to adsorbing cation and an ionic strength of 0.1 m. The edges move towards lower pH as the ratio adsorbing anion:hydrous ferric oxide increases. From data in Dzombak and Morel (1990).

Chromium

Chromium (Fig. 9-21) shows some similarities to both of the groups of elements discusse above. Under highly oxidizing conditions, the hexavalent form (chromate) is stable as a anion. It is not strongly adsorbed (adsorption edge at about pH 7, Fig. 9-20) and is therefor mobile in the environment. Under intermediate and reducing conditions, Cr(III) is the stabl oxidation state. It is insoluble in the neutral and alkaline pH ranges. It is soluble (largely a $Cr(OH)^{2+}$) under acid conditions. In general, Cr(III) species are strongly adsorbed (Fig. 9-17 Where dissolved chromium pollution occurs, the problem form is generally Cr(VI).

FIGURE 9-21 pe–pH diagram for the system Cr–O–H_2O at 25°C and one atm. Solubility is defined as a dissolved Cr activity of 10^{-4}. Data from Brookins (1988).



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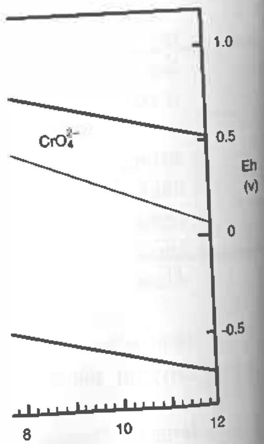


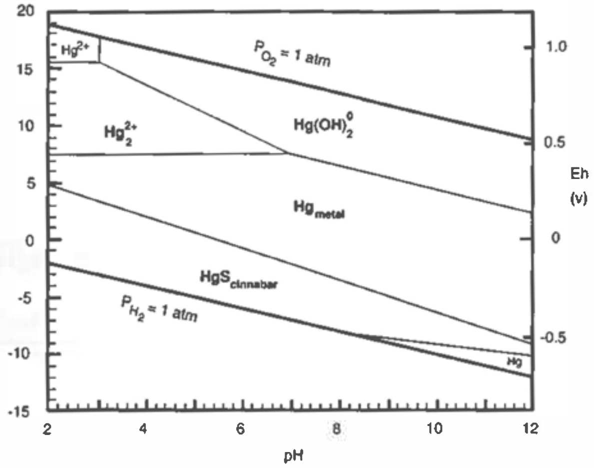


FIGURE 9-22 pe–pH diagram for the system Hg–S–O–H_2O at 25°C and one atm. Solubility is defined as a dissolved Hg activity of 10^{-6}. Total activity of sulfur species = 10^{-2}. The diagram is the same in the absence of S species, with the HgS (cinnabar) field replaced by Hg (metal). In the presence of chloride, the Hg_2^{2+} may be replaced by the insoluble mercurous chloride (calomel). Data are consistent with Allison et al. (1991).

Mercury

The chemistry of mercury in the environment is highly complex. The thermodynamically stable forms are shown in Fig. 9-22. The common soluble form is the oxidized (mercuric) Hg^{2+} ion and its hydrolysis product $Hg(OH)_2^0$, with the reduced (mercurous) Hg_2^{2+} ion being less important. Elemental mercury has a large stability field. The elemental form is volatile and slightly soluble in water. The global cycle of mercury is dominated by vapor-phase transport of Hg^0 through the atmosphere (Mason et al., 1994). Mercury is transformed by microorganisms into organic forms, notably monomethyl mercury (CH_3Hg) and dimethyl mercury [$(CH_3)_2Hg$]. These organic forms, in addition to being highly toxic, are volatile and tend to accumulate in the food chain. High concentrations of Hg in fish, which are common in polluted waters, generally result from accumulation of organomercury species. Pollutant Hg in sediments is partly transformed to organomercury species and partly to the sulfide.

Most of the metals discussed above—Cu, Zn, Cd, Pb, As, Hg, and, to a lesser extent, Se—are transformed to sulfides in anaerobic sediments. So long as conditions remain anaerobic and sulfur is available, they are relatively immobile. However, any disturbance, such as dredging, that brings the sediment into contact with oxygen will cause oxidation of the sulfides and release of the metals into solution. Cleaning up or moving contaminated sediments is a difficult problem because it may lead to oxidation and mobilization of these metals.

SUMMARY

1. To understand the behavior of any trace element in natural waters, it is essential to know the chemical form of the element in the water of interest. Anomalously high concentrations are often related to the presence of stable complexes in solution.
2. The solubility of phases containing the element as a major constituent (commonly an oxide/hydroxide, carbonate, or sulfide) provides a general upper limit to the concentration of a specific element.

This is exactly the expression we had for a non-adsorbed solute (Eq. 16–9), but with D/R substituted for D (which could be either a dispersion coefficient or a diffusion coefficient). Thus spreading by diffusion or dispersion is retarded in an analogous manner to advection. Provided dispersion is much greater than diffusion, the geometry of movement and spreading of an adsorbed solute as it moves through an aquifer will be exactly the same as that of an unadsorbed solute, but the time taken to reach a particular position and "width" will be a factor of R longer.

Adsorption affects only non-steady-state diffusion. At steady state (e.g., a constant concentration gradient between a constant source and a constant sink), there is no net uptake or release by adsorption, so adsorption has no effect on diffusion. The diffusional flux will be given by Fick's first law with no correction for adsorption.

The above discussion applies only to the limiting case of rapid, reversible, linear adsorption. Because of its mathematical convenience, the retardation equation based on the linear K_d is often used as an approximation even where these conditions do not hold. It should also be remembered that, in general, the numerical value of K_d is specific to the solute, the substrate, and the composition of the groundwater. It is not readily transferred from one experiment or situation to another.

Example 3

Suppose the pollutant in Example 2 above is adsorbed by the sediment, and the adsorption can be described by a constant K_d of 5 ℓ/kg. How long will it now take for the pollutant to reach a depth of 50 cm?

If we assume a grain density of 2.6 g/cm^3, the redardation factor, R, is

$$\left(1 + \frac{0.3}{0.7} \times 2.6 \times 5\right) = 6.57$$

The times calculated in Example 2 will be multiplied by this number. The time for 1 percent of the initial concentration to reach 50 cm will thus be 10.97 y rather than 1.67 y. Note that, for a given K_d, the retardation factor increases as the porosity decreases as a result of the factor $(1 - \phi)/\phi$. If, in this example, the porosity had been 10 percent rather than 70 percent, the retardation factor would have been 118 rather than 6.57.

REACTION PATH MODELING

Reaction path calculations, or *mass-transfer* codes, give us the successive compositions of a solution as a mineral (or several minerals) reacts with a solution or as some other process, such as evaporation of the solution, proceeds. The mass of each solid phase or gas produced or consumed is calculated. Such codes do not, in general, contain any kinetic information: They calculate changes as a function of the amount of reaction that has taken place but do not say anything about how long the reaction should take. The most widely available and widely used codes are PHREEQE (Parkhurst et al., 1980), EQ3/6 (Wolery, 1979), SOLMINEQ.88 (Kharaka et al., 1988), and MINTEQA2 (Allison et al., 1991). PHRQPITZ (Plummer et al., 1988) is a version of PHREEQE modified to include Pitzer's equations for calculations at high ionic strength (see Chapter 2); PHREEQC (Parkhurst, 1995) is an updated version of PHREEQE that includes inverse modeling analogous to NETPATH (see Chapter 12 and later in this chapter). Each of these codes was developed for a slightly different purpose, which gives them advantages and disadvantages for particular applications. PHREEQE is a relatively versatile code that can model many different types of reaction at a fixed temperature. However, the database supplied is fairly limited, particularly for trace elements, so the user may have to enter all the information for particular elements/reactions him/herself. It is not a particularly easy code for a beginner to use. MINTEQA2 is in a sense the reverse: it has an extensive database and is quite "user friendly," but the range of calculations it can perform is more limited. EQ3/6 is a large, complex, and versatile program, currently geared towards simulations associated with radioactive waste disposal. It can simulate reactions with changing temperature as well as reactions at a fixed temperature. SOLMINEQ.88 was designed particularly to simulate processes associated with petroleum basins, which implies moderately elevated temperatures and the presence of several organic species.

As an example of a reaction path calculation, let us consider the case of a mineral reacting with water. The general approach is:

1. A small increment of the mineral is dissolved.
2. A speciation-saturation program (Chapter 2) tests if the solution is supersaturated with respect to any solid phase. (The speciation–saturation program is part of the mass-transfer code. Thus each of these codes can be used for speciation–saturation calculations.)
3. If the solution is supersaturated with respect to any phase (or to specific phases specified by the user), an amount of that phase is precipitated sufficient to bring the solution into equilibrium with that phase. If the solution becomes undersaturated with respect to a previously precipitated phase, that phase redissolves to establish equilibrium.
4. An iteration procedure ensures that the solution is in equilibrium with all solid reaction products before another increment of the original mineral is dissolved.

The procedure for simulating evaporation is the same, except that increments of water are removed instead of increments of mineral being added. The calculated composition of a solution reacting with K-feldspar is shown in Figs. 16-10 and 16-11.

Although mass-transfer programs in the strict sense calculate only the path that the solution composition will follow and do not contain any rate expressions to relate reaction progress to time, it is possible to combine a mass-transfer model with a kinetic model to predict solution composition as a function of time. Examples include KINDIS (Madé et al., 1990) and PHREEQM (Appelo and Postma, 1993). There is some question as to whether our understanding of kinetics at low temperatures is sufficient for this approach to be realistic.

Example 4

A mining company proposes to dig a pit, which will be left to form a lake at the end of mining operations. The composition of the groundwater that will flow into the pit is shown in Table 16-2. The bedrock is altered granite containing calcite as the only reactive mineral. Use MINTEQA2 to predict the composition of the final lake.

In order to solve this problem, we need to make some simplifying assumptions. Some of these are:

1. A chemical equilibrium model is a suitable approximation.
2. The final lake will be in equilibrium with atmospheric oxygen and CO_2.

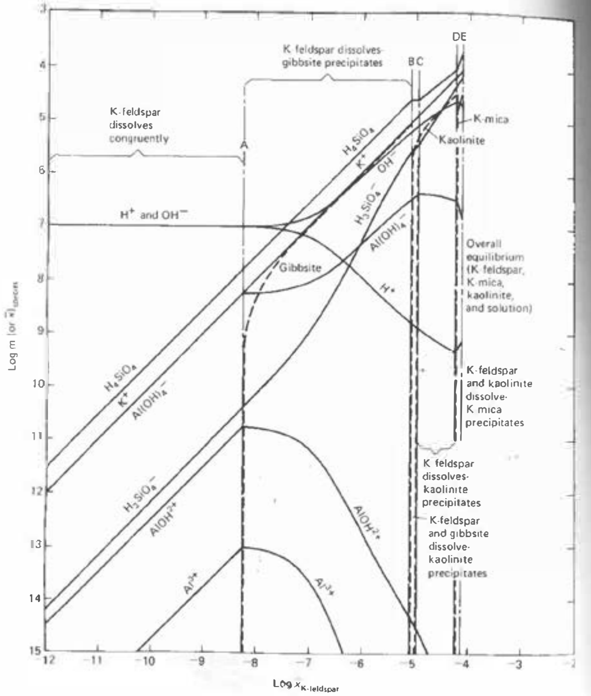
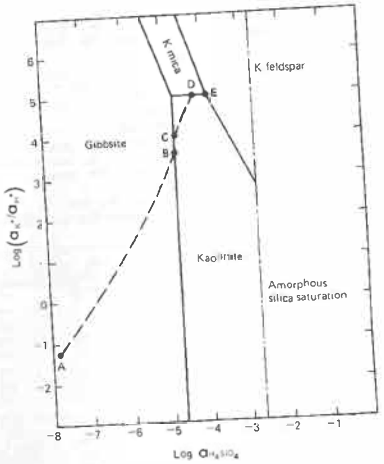


FIGURE 16-10 Concentration (m) of species in the aqueous phase (solid lines) and amounts (mol/kg H_2O) of minerals produced and destroyed (dashed lines) as K-feldspar reacts with water at 25°C and 1 atm pressure. The abscissa represents the number of moles of K feldspar destroyed per kg H_2O. The letters correspond to the points on the reaction path shown in Fig. 16-11 (Helgeson et al., 1969).

3. Reactions involving silicates can be ignored. The justification for this assumption is that the groundwater has been in contact with the silicate minerals surrounding the pit for a long time and should be close to equilibrium or at least steady state.
4. Our time span and flow rate are such that evaporation and dilution by rainfall can be neglected. In reality these would be incorporated into the model. They are omitted here for the sake of simplicity.

FIGURE 16-11 Path of solution composition (ABCDE) as K-feldspar reacts with water, plotted on a mineral stability diagram (after Helgeson et al., 1969).



The first step is to use MINTEQA2 as a speciation-saturation program only, with the water of Table 16-2 as the input. This has two purposes: (1) To see which phases are supersaturated and hence are likely to precipitate, and (2) To convert the alkalinity input into total concentration of carbonate species and concentration of the component H^+. MINTEQA2 requires the input to be in this form for further calculations. At this stage we also have to decide on an oxidation state for the Fe in the analysis. We can either input it as Fe^{2+} (which is probably the actual form), or we can input it as the oxidized species, Fe^{3+}, with the justification that the final water will be in equilibrium with atmospheric oxygen. If iron is input as Fe^{3+}, MINTEQA2 does not have to perform any redox calculations, as all the inputs are in their oxidized form. There are often advantages to minimizing the number of different reactions that the reaction path code has to consider simultaneously. The concentration of Fe is sufficiently low that the choice of oxidation state does not affect the cation–anion balance significantly. Part of the output from this first run is shown in Table 16-3.

TABLE 16-2 Composition of Inflow Water for Example 4

Na	64.2	ppm	As	0.05	ppm
K	17	ppm	Cu	0.014	ppm
Ca	151.4	ppm	Zn	1.1	ppm
Mg	54.6	ppm			
Cl	23.8	ppm	pH	7.51	
SO_4	104	ppm			
Alkalinity	12.54	meq/ℓ	T	20°C	

We can see from Table 16-3 that the water is supersaturated with respect to various phases, including calcite, dolomite, magnesite, and a range of compounds containing ferric iron (ferrihydrite, goethite, hematite, jarosite, etc.) the high saturation indices for these phases is a consequence of our decision to specify the total Fe as Fe^{3+}. The next step is to choose which phases will precipitate. We shall choose ferrihydrite as the iron compound, as it is the phase most likely to precipitate. We shall also choose calcite as a phase likely to precipitate in a natural system, but we shall not allow dolomite (or other Mg-carbonate phases) to precipitate because the kinetics of precipitation of these phases are generally slow (Chapter 3). Note that no phases containing the trace elements Cu, Zn, or As are supersaturated.

With these choices, we can now perform a second MINTEQA2 run in which we:

1. Do not specify the input pH, instead allowing MINTEQA2 to calculate the pH.
2. Specify equilibrium with a CO_2 gas phase at a pressure of 3.16×10^{-4} atm (atmospheric CO_2 pressure). We could also list O_2 at a fixed pressure of 0.2 atm, but this is unnecessary if our input does not contain any reduced species.
3. Specify calcite and ferrihydrite as *possible solids*. A possible solid is one that is allowed to precipitate if the solution is supersaturated with respect to it. Phases that are not listed in this way (or in an analogous way) will not be considered in the calculations.

Part of the output from this run is shown in Table 16-4. The solution is in equilibrium with calcite and ferrihydrite, and has a final pH of 8.88. This output would constitute our prediction for the major ions in solution. Note that the solution is still supersaturated with respect to ferric (hydr)oxides more stable than ferrihydrite (Chapter 7), and with respect to Mg-containing carbonates. 99.9 percent of the iron has been precipitated as ferrihydrite, and 98.6 percent of the calcium as calcite. The presence or absence of calcite in the bedrock would make no difference to the calculation, as calcite is precipitating and not dissolving. The main reason why so much calcite precipitated is the drop in P_{CO_2} from a value of $10^{-1.7}$ in the inflow water to $10^{-3.5}$ in the equilibrated pit lake.

So far, the only process we have considered is precipitation of supersaturated phases. Adsorption is also likely to be a significant control on trace element concentrations, particularly As, Cu, and Zn in our example (Table 16-2). As discussed in Chapter 5, adsorption can also be modeled by use of MINTEQA2. This calculation is performed after the major element chemistry has been calculated. It is necessary to specify the amount and properties of the adsorption substrate, which requires further assumptions. The details of these calculations are not presented here. A reasonable set of assumptions would be that ferrihydrite is the adsorbing phase, the amount present is equal to the amount precipitated in the previous modeling step, and its properties are the same as those of ferrihydrite used in laboratory experiments by Dzombak and Morel (1990). The Dzombak and Morel numbers are supplied as a data file with MINTEQA2. Calculations based on these assumptions indicate that adsorption should greatly reduce the concentrations of arsenic, copper, and zinc.

Application to Contaminant Transport in Groundwater

It has become recognized in recent years that human activities are introducing contaminants into groundwater systems on an enormous scale. Examples include leaching from municipal landfills, hazardous waste burial sites, mine tailings, and various spills, both deliberate and accidental. Agriculture itself often causes contamination of groundwater by fertilizers (notably nitrate) and pesticides. A great deal of effort is currently being put into modeling the

TABLE 16-4 Output from the MINTEQA2 Equilibration Calculation for Example 4 (The output file has been greatly condensed.)

```
_____________________________ PART 1 of OUTPUT FILE _____________________________
Example 4: Equilibration with atmosphere and solid phases


---------------------------------------------------------------------------------
  Temperature (Celsius):  20.00
  Units of concentration: MG/L
  Ionic strength to be computed.
  If specified, carbonate concentration represents total inorganic carbon.
  Do not automatically terminate if charge imbalance exceeds 30%
  Precipitation is allowed only for those solids specified as ALLOWED
    in the input file (if any).
  The maximum number of iterations is:  40
  The method used to compute activity coefficients is: Davies equation
  Intermediate output file
---------------------------------------------------------------------------------
INPUT DATA BEFORE TYPE MODIFICATIONS
   ID        NAME           ACTIVITY GUESS       LOG GUESS    ANAL TOTAL
   330   H+1                  1.000E-07           -7.000      1.370E+01
    61   H3AsO4               3.548E-07           -6.450      5.000E-02
   150   Ca+2                 3.802E-03           -2.420      1.514E+02
   180   Cl-1                 6.761E-04           -3.170      2.380E+01
   231   Cu+2                 2.188E-07           -6.660      1.400E-02
   281   Fe+3                 2.291E-05           -4.640      1.270E+00
   460   Mg+2                 2.239E-03           -2.650      5.460E+01
   410   K+1                  4.365E-04           -3.360      1.700E+01
   500   Na+1                 2.818E-03           -2.550      6.420E+01
   732   SO4-2                1.072E-03           -2.970      1.040E+02
   950   Zn+2                 1.698E-05           -4.770      1.100E+00
   140   CO3-2                9.333E-05           -4.030      7.859E+02
     2   H2O                  1.000E+00             .000      0.000E-01

      Charge Balance: UNSPECIATED
        Sum of CATIONS=  2.900E-02 Sum of ANIONS =  2.906E-02
        PERCENT DIFFERENCE =  1.065E-01  (ANIONS - CATIONS)/(ANIONS + CATIONS)

  Type V - POSSIBLE SOLIDS
     ID          NAME          CALC MOL        LOG MOL    NEW LOGK      DH
  5015001   CALCITE          1.937E+02        2.287      8.446       2.585
  2028100   FERRIHYDRITE     6.817E+02        2.834     -4.891        .000
_________________________________________________________________________________
_____________________________ PART 5 of OUTPUT FILE _____________________________

              ---------------------------------------------
              -------EQUILIBRATED MASS DISTRIBUTION-------

                              DISSOLVED              SORBED              PRECIPITATED
  IDX       NAME          MOL/KG    PERCENT     MOL/KG    PERCENT      MOL/KG    PER-
 CENT

  330   H+1            4.365E-03    100.0    0.000E-01      .0     0.000E-01     .0
   61   H3AsO4         3.527E-07    100.0    0.000E-01      .0     0.000E-01     .0
  950   Zn+2           1.685E-05    100.0    0.000E-01      .0     0.000E-01     .0
  180   Cl-1           6.721E-04    100.0    0.000E-01      .0     0.000E-01     .0
  231   Cu+2           2.206E-07    100.0    0.000E-01      .0     0.000E-01     .0
  732   SO4-2          1.084E-03    100.0    0.000E-01      .0     0.000E-01     .0
  460   Mg+2           2.248E-03    100.0    0.000E-01      .0     0.000E-01     .0
```

(Continued)

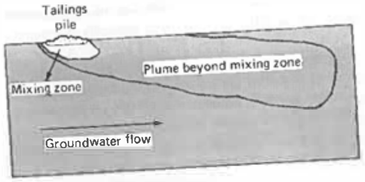
```
410  K+1          4.353E-04  100.0  0.000E-01     .0   0.000E-01     .0
500  Na+1         2.796E-03  100.0  0.000E-01     .0   0.000E-01     .0
281  Fe+3         1.853E-08     .1  0.000E-01     .0   2.275E-05   99.9
150  Ca+2         5.213E-05    1.4  0.000E-01     .0   3.730E-03   98.6
140  CO3-2        4.727E-03   55.9  0.000E-01     .0   3.730E-03   44.1
  2  H2O          9.297E-06  100.0  0.000E-01     .0   0.000E-01     .0

     Charge Balance: SPECIATED
       Sum of CATIONS =  7.178E-03 Sum of ANIONS   7.239E-03
       PERCENT DIFFERENCE =  4.291E-01  (ANIONS - CATIONS)/(ANIONS - CATIONS)
     EQUILIBRIUM IONIC STRENGTH (m) =   1.029E-02
     EQUILIBRIUM pH                 =   8.879

____________________________PART 6 of OUTPUT FILE______________________________
Saturation indices and stoichiometry of all minerals
    ID #      NAME       Sat. Index          Stoichiometry in [brackets]
 5015000 ARAGONITE        -.154     [  1.000] 150  [  1.000] 140
 5015001 CALCITE           .000     [  1.000] 150  [  1.000] 140
 5015002 DOLOMITE         1.654     [  1.000] 150  [  1.000] 460  [  2.000] 140
 2028100 FERRIHYDRITE     0.000     [ -3.000] 330  [  1.000] 281  [  3.000]   2
 2028102 GOETHITE         4.210     [ -3.000] 330  [  1.000] 281  [  2.000]   2
 6015001 GYPSUM          -2.897     [  1.000] 150  [  1.000] 732  [  2.000]   2
 3028100 HEMATITE        13.405     [ -6.000] 330  [  2.000] 281  [  3.000]   2
 5015003 HUNTITE           .812     [  3.000] 460  [  1.000] 150  [  4.000] 140
 6041002 JAROSITE K      -7.386     [ -6.000] 330  [  1.000] 410  [  3.000] 281
                                    [  2.000] 732  [  6.000]   2
 3028101 MAGHEMITE        3.397     [ -6.000] 330  [  2.000] 281  [  3.000]   2
 5046002 MAGNESITE        1.156     [  1.000] 460  [  1.000] 140
 2023101 TENORITE         -.815     [ -2.000] 330  [  1.000] 231  [  1.000]   2
 5095000 SMITHSONITE      -.861     [  1.000] 950  [  1.000] 140
 5095001 ZNCO3, 1H2O      -.546     [  1.000] 950  [  1.000] 140  [  1.000]   2
 2095005 ZNO(ACTIVE)      -.449     [ -2.000] 330  [  1.000] 950  [  1.000]   2
 2095006 ZINCITE          -.552     [ -2.000] 330  [  1.000] 950  [  1.000]   2
 5023101 MALACHITE       -2.691     [  2.000] 231  [  2.000]   2  [  1.000] 140
                                    [ -2.000] 330
 3028102 LEPIDOCROCIT     3.520     [ -3.000] 330  [  1.000] 281  [  2.000]   2
________________________________________________________________________________
```

behavior of contaminants in the subsurface, both for predicting the fate of and designing remediation strategies for existing contaminants and for designing and locating disposal sites for future waste, particularly high-level radioactive waste.

Before any detailed geochemical modeling can be attempted, the hydrology of the area in question, particularly groundwater flow paths and velocities, must be established. This is by no means a trivial requirement; the information required for an adequate hydrologic model may be greater than that required for a chemical model, and the mathematical formulation of the hydrologic model may be extremely complex.

For modeling purposes, it is often convenient to divide the region to be studied into a source, a mixing zone (*near field*, in the terminology of radioactive waste disposal), and a relatively undisturbed aquifer or aquifers (*far field*). This is illustrated conceptually in Fig. 16-12 for a mill tailings pile. A real example of modeling applied to a uranium mill tailings pile is given by White et al. (1984) and Narasimhan et al. (1986). The source is the downward movement of solutions from the tailings pile. These solutions are oxygenated and highly acidic from the processing used in the mill and contain high concentrations of iron and several trace elements such as uranium, molybdenum, and selenium.

FIGURE 16-12 Schematic illustration of migration of contaminants from a uranium mill tailings pile.



Groundwaters are typically mildly alkaline and may be oxidizing or reducing. When the
acid tailings solution enters the aquifer, it reacts chemically with the groundwater and with the
minerals of the aquifer. Calcite dissolves, gypsum may precipitate, and iron and aluminum
hydroxides precipitate, coprecipitating trace metals with them. Chemical reactions such as
these can be modeled successfully by a program such as PHREEQE, MINTEQ, or EQ3/6. The
mixing zone, where the major chemical reactions take place, is commonly a relatively small
volume, and the hydrology of such a small volume can be modeled in a relatively simple way.

Beyond the mixing zone, the groundwater is more or less in equilibrium with the min-
erals of the aquifer. Dissolution and precipitation are no longer major processes, and mod-
eling focuses on hydrology/water movement plus hydrodynamic dispersion and on
relatively simple chemical processes such as adsorption, radioactive decay, and, for some
organic compounds, biodegradation.

An additional problem with modeling of contaminant transport is the question of how to
treat uncertainty. One can never know with certainty the porosity, permeability, and disper-
sivity, for example, at all points in an aquifer. One can make estimates for the regions in which
data are missing and, using them, calculate, for example, a travel time for a particular solute
between two locations. For problems such as disposal of high-level radioactive waste, it is
important to know the uncertainty associated with the travel time as well as the "best esti-
mate." Increasingly, *stochastic modeling* is being used to assess uncertainty. Instead of single
values being assigned to the properties of each location in the aquifer, a statistical distribution
of properties is assigned, and the model generates a statistical distribution of travel times or
whatever other output is required.

CHEMICAL EVOLUTION OF GROUNDWATER

The reaction path modeling discussed above has been "forward" modeling in that we posed
the problem in the form: "Suppose we have water A and allow it to react with minerals B and
C, what will be the final composition of the water?" For understanding the chemical compo-
sition of groundwater, we are generally presented by the "inverse" problem (Plummer, 1992):
we know the composition of the final water, the problem is to deduce the reactions that gave
rise to it. One approach is simply to solve the forward problem repeatedly, changing the iden-
tity and amount of the minerals reacting until a "match" is achieved. Alternatively, one can use
the code NETPATH (Plummer et al., 1991) or PHREEQC (Parkhurst, 1995) to solve the
inverse problem directly. The use of NETPATH to solve a mass balance problem was dis-
cussed in Chapter 12. The input is an initial water composition, a final water composition, and

a list of phases that may dissolve, precipitate, or both. The output is a list of all the possible reactions involving the listed minerals that satisfy the mass balance constraints. NETPATH also considers isotopic balance for ^{13}C, ^{14}C, ^{34}S, D, T, ^{18}O and ^{87}Sr, and includes WATEQ4F as a subroutine to test whether the reactions deduced from mass balance are chemically reasonable. It would not be reasonable, for example, to postulate that gypsum precipitates from a solution that is undersaturated with respect to gypsum.

An excellent example of this type of modeling is the study by Plummer et al. (1990) of the chemical evolution of groundwater in the Madison aquifer as it moves several hundred km eastward from recharge areas in Montana and Wyoming. The chemical evolution of the water was consistent with dissolution of gypsum and dolomite, precipitation of calcite, and oxidation of organic matter. That set of reactions explained not only the major element chemistry, but also the isotopes of carbon and sulfur.

A major problem with NETPATH-type modeling, particularly of silicate weathering reactions, is that solutions are rarely unique. Several different sets of minerals can usually be found that satisfy the constraints. Also, depending on the number of solid phases chosen, there may be no solution or an indeterminately large number of solutions. The code is thus a tool to be used in conjunction with geologic insight and judgment: it does not provide simple, unique answers. The inclusion of isotopes may greatly constrain the number of possible answers, provided sufficient isotopic data are available.

REVIEW QUESTIONS

1. Suppose you had a 1 mm wide fracture in an igneous rock, and the concentration of a contaminant in the fracture were kept at a constant value (say by rapid flushing). How long would it take for a mass of contaminant equal to the mass present in the fracture at any instant to diffuse into the rock matrix? Assume a porosity for the matrix of 0.01 and an effective diffusion coefficient of $1 \times 10^{-7}\ cm^2 s^{-1}$.
2. Suppose you assume instead (Problem 1) that the fluid in the fracture were not moving. Estimate how long it would take for half the material in the fracture to diffuse into the rock matrix. How long would it take if the fracture width were 0.1 mm?

   Note: The analytical solution to this problem is by no means simple. You could (a) make an educated guess based on example 1 above; (b) construct a simple numerical model; or (c) (if you have the background) construct a finite difference model.
3. The following analyses (from Plummer et al., 1990) represent two wells from the Madison aquifer in Montana that lie approximately along a flowline. The aquifer contains limestone, dolomite, and occasional evaporites. Use NETPATH to come up with a set (or more than one set) of reactions that could account for the difference. Do you think the reactions are plausible?

	$T(°C)$	pH	Ca	Mg	Na	K	Cl	SO_4	ΣCO
Well 1	11	7.58	1.87	1.15	0.10	0.02	0.05	1.46	3.31
Well 2	32	7.08	6.50	3.96	3.44	0.31	1.89	10.32	3.72

4. In Example 4 above, suppose the pit lake were to stratify, forming an anoxic hypolimnion (Chapter 8). Predict the chemical composition of the anoxic waters. Make your assumptions clear, and discuss how reasonable these assumptions are.

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DOCUMENT

2

Predicting Hydrology of Fractured Rock Masses from Geology

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Fracture network connectivity often dominates movement rate, flow volume, and mass transport through rock masses. These networks influence the effectiveness of petroleum reservoir development, safe disposal of nuclear waste, delineation of water supply or establishment of well-head protection plans, recovery from geothermal reservoirs, solution mining, construction of underground openings, and the remediation of contaminated rock. Well tests can provide a great deal of useful information on the hydraulic properties of fracture systems, but they are often expensive or logistically infeasible. These tests also may not provide an accurate description of the hydrologic properties of the rock volume under consideration. Methods to model fractured rock can be improved by quantifying the relation between geologic parameters and the hydrologically conductive fractures. This study illustrates the application of four statistical and pattern recognition methods—evaluation of correlation coefficients, contingency table analysis, multivariate regression, and neural net analysis. The data for the study consist of borehole and well-test information from eight boreholes used for characterizing a proposed low-level radioactive waste repository in Wake County, North Carolina. The analyses show that high localized flow rates are related to the presence of increased fracture intensity, and that this intensity is controlled by a complex interplay of structural geology and lithology. Some of the initial hypotheses concerning the relation of geology to hydrology were not substantiated by the data, leading to a refined conceptual model that differed in significant ways from the initial model. Although the techniques used are of general applicability, the precise nature of the correlation between geology and hydrology is site dependent.

1. INTRODUCTION

1.1 Overview

Fractures are geologic features that form networks capable of transporting fluids through rock over long distances. The rate of movement, the volume of flow, the amount of mass transport through the system interconnected fractures affect petroleum reser development, safe disposal of nuclear waste, delineatio water supply or establishment of well-head protec plans, recovery from geothermal reservoirs, the efficie of solution mining, the construction of undergro openings, and the remediation of contaminated rock.

It is common for engineers and hydrologists to em hydrologic testing to directly characterize fracture netw flow parameters. However, well tests are often expen

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or logistically infeasible. For example, the number and spatial reach of wells drilled from an offshore oil platform are very much restricted. This may cause direct hydrologic test results to be very sparse for the volume of rock under consideration. It also presents a problem because hydrologic heterogeneity is often quite significant, so that and, therefore, a few tests may not provide an accurate description of the hydrologic properties of the large volume of rock under consideration. Such a situation makes it necessary to infer parameters from the well or boreholes to a much larger volume of rock.

There are two broad approaches to modeling flow and transport in fractured rock [*National Research Council,* 1996]: the Discrete Fracture Network (DFN) approach and the Stochastic Continuum (SC) approach. Both methods have advantages and disadvantages.

DFN models require the specification of the geometry, location, and hydraulic properties of the fractures that play a significant role in the rock permeability.

SC models need permeability and porosity values that reflect the local matrix and fracture systems' effective properties at the scale and shape of the numerical grid. SC models incorporate geology to delineate large-scale statistically homogeneous regions, often referred to as *domains* or *zones*. Parameter values within these domains can be assigned according to statistical distributions or conditioned to geologic parameters. Often, the relation between mappable geology and values of effective permeability is not well understood. Parameter assignment within each domain is carried out using a spatial statistical model or an inversion that matches known well test results, but is constrained elsewhere to statistical parameters only [*Zimmerman et al., 1998*]. Better geologic conditioning of the parameter values within zones and better definition of zones can greatly improve model accuracy [*La Pointe et al.*, 1996; *National Research Council,* 1996].

Over the past decade, DFN models [*Hudson and La Pointe,* 1980; *Long et al.*, 1982; *Dershowitz,* 1984; *Endo et al., 1984; Robinson,* 1984; *Smith and Schwartz, 1984*] have evolved to successfully address problems of regional fracture network connectivity [*Cacas et al.,* 1990a,b; *Dershowitz et al.*, 1992; *Swaby and Rawnsley,* 1996]. The models represent fractures as polygons with flow and transport properties. However, the specification of these models relies upon accurately describing the geologic context of the subset of fractures that contribute to large-scale flow. This subset of fractures constitutes the network of *conductive* fractures. As detailed surveys of wellbores prove, only a portion, often less than 10% [*National Research Council*, 1996] play a role in flow at the scale of contaminant dispersal, energy production, or containment of nuclear waste. It is the intensity, geometry, and fluid-flow properties of this conductive subset that control the important behavior of fracture-dominated flow systems.

Thus, better understanding of the geologic habitat of conductive fractures could lead to improved DFN modeling, as well as a better understanding of why some fractures play a significant role in regional flow, while others play a limited, or insignificant role.

The attractiveness of geologically conditioning DFN or SC models rests on the presumption that hydrology relates to geology. By understanding the geologic characteristics that are associated with hydrologic variability, it is possible to describe the conductive fracture network or assign values of permeability (or other properties) at unsampled locations based upon the geologic characteristics.

The geologic approach is very appealing, since it is much more flexible in handling hydrologic variability as a result of variability in underlying geology than any zonal statistical model. This is because the geologic approach need not conform to overly simplistic statistical models. Moreover, a demonstrated connection between mappable geology and flow modeling is important in many licensing applications for proposed waste repositories or other facilities. Another advantage is that the geology is often known with reasonably high accuracy and resolution throughout the site.

However, the attempt to relate flow in fractured rock masses to underlying geology has proven challenging, particularly in fracture-dominated flow systems. Fracture network connectivity often controls flow and transport. This means that local geologic conditions might be affected by the properties of individual fractures and may not correlate to the larger-scale fracture network connectivity.

The current study attempts to understand the geologic habitat of fractures that play an important role in regional flow and mass transport. The focus of the study is a preliminary site investigation of a proposed low-level nuclear waste repository in Wake County, North Carolina. Licensing of the site requires modeling of possible movement of radionuclides through the rock and soil.

The goal of this work was to investigate the interrelation of hydrologic behavior and geologic characteristics by using multivariate analysis or other techniques, as appropriate, to help prepare the initial site conceptual model and support the development of the preliminary groundwater flow simulations. The identification of key geologic parameters was also important. These parameters needed to be measured in a manner sufficient for subsequent hydrologic modeling and so as to identify how data collection protocols might be altered in order to obtain the necessary data.

The problem of relating geology to hydrology is one of pattern recognition. Powerful and sophisticated tools to recognize patterns and correctly classify new data into proper groups are in common use in many disciplines. These tools differ in mathematical assumptions and outcomes, but all share the ability to classify data into categories. Section 1.4 below describes the methodology employed in this study in greater detail.

1.2 Data

A thorough data set was obtained for this study from geochemical surveys, hydrophysical logging, packer tests, and geologic logging. The data came from a series of eight wells, aligned from west to east. The line formed by these wells transects a prominent fault north-striking a normal fault (Figure 1). Wells W206 through W208 lie to the east of the fault in the footwall of the normal fault. Wells W201 through W205 lie in the hanging wall. As shown in Figure 1, well W205 cuts through the fault plane. Each of these boreholes was carefully logged to record both the lithologic characteristics and the attributes of any fractures present. Subsequently, the core and the borehole imagery was interpreted to create a data set in which fractures were identified, and their measured depths, orientations, apertures, and types recorded. Lithologic information was also recorded. This included grain-size classification, ranging from conglomerate to claystone, as well as the orientation and measured depth of contacts separating strata of contrasting lithology.

Hydrophysical anomalies were identified as part of the testing and logging program carried out in the eight wells. Such anomalies were determined as follows. First, a borehole was filled with deionized water and a logging tool to measure electrical conductivity is placed in the borehole. Next, the nonconductive deionized water was slowly pumped out, which allowed the conductive groundwater to flow through fractures or other permeable pathways into the borehole and be sensed by the logging tool. Continuous recording of the conductivity made it possible to identify locations and rate of groundwater flow into the borehole. The term "strength," as used in this study, refers to the magnitude of the conductivity change between the nonconductive, deionized water and the inflowing groundwater. The magnitude of the anomaly is a function of flow rate, and is used as a surrogate for fracture transmissivity or local wellbore permeability. The tool used in this study has a 1 ft (0.3 m) resolution. Together with image logs, it is possible to relate hydrophysical anomalies to fractures or other geologic features within the 1 ft intervals. Figure 2 summarizes the interpreted lithology, and shows the location and geometric aperture of detected fractures, as well as the location and magnitude of flow for hydrophysical anomalies. Figure 3 and Table 1 show the directly measured and derived geologic parameters used in this study. Parameters related to the four nearest fractures were included to account for the 1 ft resolution of the hydrophysical logs, and for any small misregistration among the hydrophysical logs, the borehole imagery, and the core.

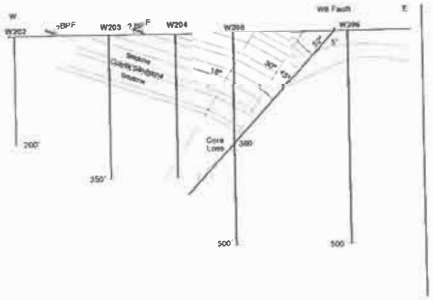

Figure 1. Geologic cross section along trench GM-1. Trench is oriented along an east-west axis. The normal fault, denoted as W8, strikes approximately north-south.

1.3 Initial Hypotheses

A preliminary focus of efforts at the Wake County site was to clarify the role of jointing and faulting in the site-scale hydrology. It was thought that fracture intensity at the site might be related to depth, weathering, structural deformation, and structural position. Thus, the study focused on evaluating some initial hypotheses concerning the relations between site geology and conductive flow features. These hypotheses are:

1. Hydrophysical anomalies are caused by fracture flow.
2. Fracture intensity is greater in the hanging-wall deformation zone.
3. Proximity to contacts between strongly contrasting lithological units leads to an increase in fracturing.
4. Fracture intensity relates to lithology.
5. Fracture intensity changes with depth/elevation because of weathering or lithostatic effects.
6. None of the above.

1.4 Methodology

A number of statistical and pattern-recognition techniques were applied to the data in order to investigate possible relations between geologic parameters and fracture flow. These studies were designed not only to test existing hypotheses, but also to uncover other unsuspected relations between geologic parameters and the

Table 1. Directly measured and derived geologic parameters.

Directly Measured Parameters	**Symbol**	**Dimensions**
Fracture Parameters		
Measured depth to fracture	MDF	Feet
Fracture dip and dip direction	DIP,DPDIR	Degrees
Fracture type: Shear or bedding	TYPE	
Fracture Aperture	AP	Inches
Lithologic Parameters		
Lithologic classification, based on grain size, gradated from 1 to 9 (1 being coarsest; 9 being finest): Conglomerate (Cnglom) = 1 Very coarse sandstone (VCrsSS) = 2 Coarse sandstone (CrsSS) = 3 Medium sandstone (MedSS)= 4 Fine sandstone (FineSS)= 5 Very fine sandstone (VFineSS)= 6 Siltstone (SiltS) = 7 Mudstone (MudStone) = 8 Claystone (Claystone) = 9	LITH	Grain size
Measured depth to contact between lithologic units	MDCON	Feet
Orientation of contact between lithologic units	CONDIP, CONDPDIR	Degrees
Layer (lithologic unit) thickness , distance measured vertically	UTHICK	Feet
Dip of contact above anomaly	DIP_A	Degrees
Dip of contact below anomaly	DIP_B	Degrees

Table 1(continued).

Derived Parameters		
Distance from hydrophysical anomaly to four nearest fractures	D1, D2, D3, D4	Feet
Apertures of four fractures nearest to a hydrophysical anomaly	W1, W2, W3, W4	Inches
Lithology of four nearest fractures (ranging from conglomerate to mudstone, 1 to 8)	L1, L2, L3, L4	Grain size
Depth of four nearest fractures	MD1, MD2, MD3, MD4	Feet
Lithology contrast between layer containing hydrophysical anomaly lithology and layer above; grain-size class of layer above used for computation	LCA	Dimensionless
Lithology contrast between layer containing hydrophysical anomaly lithology and layer below; grain-size class of layer above below for computation	LCB	Dimensionless
Absolute contrast above; computed as ABS(LCA)	ALCA	Dimensionless
Absolute contrast below; computed as ABS(LCB)	ALCB	Dimensionless
Total contrast between lithological unit containing anomaly and units above and below; computed as LCA+LCB	TC	Dimensionless
Total absolute contrast between lithological unit containing anomaly and units above and below; computed as ALCA+ALCB	ATC	Dimensionless
Distance from anomaly to nearest upper contact; computed as distance perpendicular to contact interface	CDA	Feet
Distance from anomaly to nearest lower contact; computed as distance perpendicular to contact interface	CDB	Feet
Minimum distance to contact; computed as MIN(CDA, CDB	CMIN	Feet
Grain size contrast with nearest unit	C_NEAR	Dimensionless
Apparent distance to upper contact	APCDA	Feet
Apparent distance to upper contact	TDIST_MIN	Feet
Apparent distance to lower contact	APCDB	Feet
Angular difference between upper and lower contact; computed as DIP_B - DIP_A	UNCONF	Degrees
Absolute value of UNCONF	ABS(UNCF)	Degrees
Bed thickness	THICK	Feet

hydrophysical anomalies. The following statistical techniques were used:

1. Evaluation of correlation coefficients among all parameters.
2. Contingency table analysis.
3. Multivariate regression.
4. Neural net analysis.

Correlation coefficients are very useful in examining the first-order relations between continuous variables such as the strength of the hydrophysical anomaly and its proximity to the boundary of a contrasting lithologic unit, or between the depth of a fracture and its aperture. These coefficients are also important in gaining an understanding of which variables may be redundant. Identifying redundant variables is important when data are sparse. When there are more variables—degrees of freedom—than hydrophysical anomalies, it is possible to predict the anomalies with a good degree of accuracy without actually determining any significant relations among the parameters.

Two-way contingency table analysis is a method for looking at the correlation among class or ordinal variables. It is also useful for examining relations between a parameter-like lithologic unit and a hydrophysical anomaly.

Contingency table analysis and correlation coefficients examine relations between pairs of variables. Multiple regression takes into account the combined relations among many variables. Multiple regression assumes that the dependent variable is a linear combination of independent (uncorrelated) variables.

Neural nets are the most complex of the methods used to investigate the relations among dependent variables and hydrophysical anomalies. This approach does not assume a simple or hypothesized model among the variables, nor does it require linear independence. Unlike multiple regression, it can also include class or ordinal variables such as lithologic type. Since the variable of interest, i.e., the hydrophysical anomaly flux rate, is a continuous variable, a Generalized Regression Neural Network (GRNN), was employed. This type of network architecture has proven very useful for this type of application [*Ward*, 1996].

2. RESULTS

2.1 Correlation Coefficients

Table 2 shows the correlation coefficients for all of the independent variables with hydrophysical anomaly strength. This strength has been expressed in two ways: the arithmetic strength, which is the actual measured value, and the base-ten logarithm of the measured strength. The logarithmic transformation of a variable reduces the impact of extreme values, which may be outliers or spurious measurements.

Correlation coefficients vary between −1.0 (perfect anticorrelation) and +1.0 (perfect correlation). The statistically significant correlations at the 95% level in Table 2 are those in which the absolute value of the

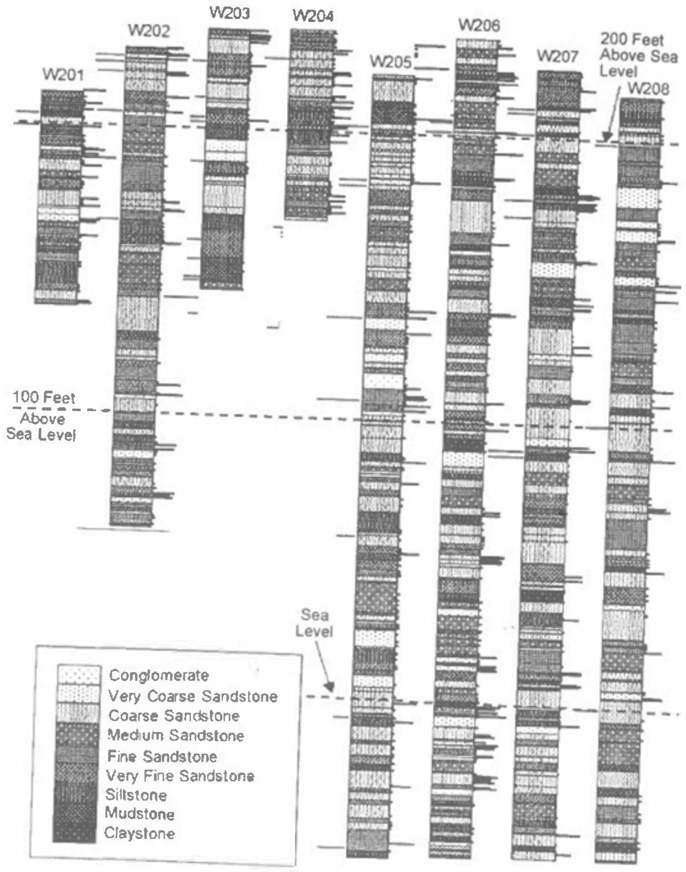

Figure 2. Summary of lithology, fractures, and hydrophysical anomalies. For each borehole, the location of hydrophysical anomalies and fractures are shown by horizontal lines. The length of the line to the left of the borehole is proportional to the logarithm of the hydrophysical anomaly magnitude, while the length of the line to the right of the borehole is proportional to the logarithm of the fracture aperture. In both cases the lines represent relative, not absolute lengths.

correlation coefficient is greater than or equal to 0.35.

This table shows that the anomaly strength and the log of the anomaly strength are positively correlated with the fracture width (aperture), the lithology of the unit in which the hydrophysical anomaly occurs, and the surrounding lithologic units, their contrast, and the dip of the contact between lithologic units. The positive correlation with lithology means that finer-grained lithological units have stronger anomalies. The positive correlation with the absolute total contrast (ATC) implies that stronger anomalies tend to be in lithologies, unlike the units immediately above and below. The correlation with contact dip may reflect structural disruption in the hanging wall of the fault, but other explanations may also be possible. The log of the anomaly strength is negatively correlated with the distance to the nearest fractures (in other words, the closer the fractures to the anomaly and the more there are of them, the stronger the anomaly).

Table 2. Correlation coefficients for flow anomaly and $\log_{10}$(anomaly) with geological parameters. Absolute values of the coefficient equal to 0.35 or greater are significant at the 95% level.

Variable	Anomaly	Log_{10} (anomaly)
W2	0.36	0.53
ALCA	0.31	0.48
ATC	0.20	0.47
W3	0.40	0.40
LITH	0.08	0.31
CONDIPB	0.47	0.27
CNEAR	−0.02	0.27
ALCB	0.00	0.23
W1	0.00	0.19
W4	−0.03	0.18
LCB	0.15	0.16
LCA	−0.25	0.15
LITHA	0.38	0.14
LITHB	−0.11	0.13
MDF	0.19	0.08
CONDIPA	0.23	0.01
APCDB	−0.01	0.00
CDB	−0.04	−0.02
CDA	0.17	−0.12
APCDA	0.19	−0.13
CMIN	0.08	−0.25
D1	−0.12	−0.34
D4	−0.15	−0.39
D3	−0.18	−0.40
D2	−0.18	−0.45

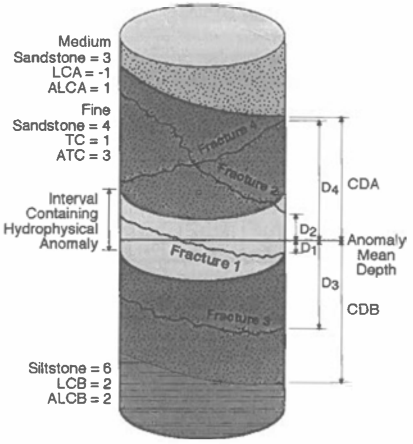

Figure 3. Derived parameters used in the statistical analyses. Table 1 provides additional explanation of these and other parameters.

2.2 Contingency Tables

Contingency tables were computed for various combinations of variables. This type of analysis is useful for determining whether a variable of interest shows up with unusually high or low frequency in some other variable class. For example, do siltstones have an unusually high frequency of fractures or hydrophysical anomalies that is out of proportion to their stratigraphic percentage?

Tables 3, 4, and 5 provide overall lithology and fracture intensity data for the eight wells. Table 3 shows how lithology varies among the eight wells. This Table illustrates that fine-grained lithological layers, particularly siltstone, increase eastward from W201 to W205, where such layers reach upwards of 45% of the total amount. They decrease abruptly in the three wells to the east of W205.

Tables 4 and 5 summarize the fracture intensity by lithology and well. These tables show that fractures in the western wells (W201 through W203) tend to reside in the coarse sandstone, while in the wells nearer to the fault, the fractures tend to occur in the siltstones. However, the

Table 3. Lithology statistics by well.

	Total Thickness (inches) of Lithological Layers Within Wells									
	Lithology									
Well No.	1 Cnglom	2 VCrsSS	3 CrsSS	4 MedSS	5 FineSS	6 VFineSS	7 SiltSt	8 MudStone	9 ClayStone	Total
W201		50.25	146.74	218.29	108.29	74.42	177.11	79.44		854.54
W202			188.71	432.06	420.76	209.13	550.51	147.26		1948.43
W203		72.8	175.94	351.29	9.41	34.18	354.3	88.82		1086.74
W204		4.43	117.38	107.36	63.42	74.03	326.4	29.17		722.19
W205	30.71	220.76	479.08	1388.54	590.14	299.59	3403.86	648.01	70.87	7131.56
W206	66.35	186.64	304.61	912.62	484.35	611.72	1286.1	349.94	46.55	4248.88
W207	266.82	194.12	349.49	814.3	434.02	546.04	1814.42	402.63		4821.84
W208	110.12	67.26	189.86	474.12	1822.33	759.82	1584.26	429	43.26	5480.03
Total	474	796.26	1951.81	4698.58	3932.72	2608.93	9496.96	2174.27	160.68	26294.21
	Percent of Thickness of Lithological Layers Within Wells									
	Cnglom	VCrsSS	CrsSS	MedSS	FineSS	VFineSS	SiltSt	MudStone	ClayStone	
W201		5.88	17.17	25.54	12.67	8.71	20.73	9.30		
W202			9.69	22.17	21.59	10.73	28.25	7.56		
W203		6.70	16.19	32.33	0.87	3.15	32.60	8.17		
W204		0.61	16.25	14.87	8.78	10.25	45.20	4.04		
W205	0.43	3.10	6.72	19.47	8.28	4.20	47.73	9.09	0.99	
W206	1.56	4.39	7.17	21.48	11.40	14.40	30.27	8.24	1.10	
W207	5.53	4.03	7.25	16.89	9.00	11.32	37.63	8.35		
W208	2.01	1.23	3.46	8.65	33.25	13.87	28.91	7.83	0.79	

Table 4 Total number of fractures by lithology within wells, independent of aperture.

	Total No. of Fractures by Lithology within Wells									
	Lithology									
Well No.	1 Cnglom	2 VCrsSS	3 CrsSS	4 MedSS	5 FineSS	6 VFineSS	7 SiltSt	8 MudStone	9 ClayStone	Total
W201		7	6	32	5	3	16	16		85
W202			22	30	9	2	19	10		92
W203		1	4	36	0	1	10	1		53
W204		0	16	19	11	16	37	2		101
W205	3	36	57	124	60	22	203	82	5	592
W206	2	10	24	54	19	17	82	54	7	269
W207	13	13	27	66	34	14	55	41		263
W208	5	3	7	37	46	40	69	43	13	263
Total	23	70	163	398	184	115	491	249	25	1718
	Percent of Total Fractures by Lithology within Wells									
	Cnglom	VCrsSS	CrsSS	MedSS	FineSS	VFineSS	SiltSt	MudStone	ClayStone	
W201		8.24	7.06	37.65	5.88	3.53	18.82	18.82		
W202			23.91	32.61	9.78	2.17	20.65	10.87		
W203		1.89	7.55	67.92	0.00	1.89	18.87	1.89		
W204		0.00	15.84	18.81	10.89	15.84	36.63	1.98		
W205	0.51	6.08	9.63	20.95	10.14	3.72	34.29	13.85	0.84	
W206	0.74	3.72	8.92	20.07	7.06	6.32	30.48	20.07	2.60	
W207	4.94	4.94	10.27	25.10	12.93	5.32	20.91	15 59		
W208	1.90	1.14	2.66	14.07	17.49	15.21	26.24	16.35	4.94	

Table 5. Total number of fractures by lithology within wells for apertures > 0.03 in.

	Total No. of Fractures > 0.03 in. by Lithology within Wells									
	Lithology									
Well No.	1 Cnglom	2 VCrsSS	3 CrsSS	4 MedSS	5 FineSS	6 VFineSS	7 SiltSt	8 MudStone	9 ClayStone	Total
W201		2	2	4	2	0	2	6		18
W202			4	8	1	0	10	1		24
W203		0	0	5	0	0	4	0		9
W204		0	4	5	2	2	8	0		21
W205	0	3	3	9	6	1	27	9	1	59
W206	0	3	3	11	5	3	20	22	4	71
W207	4	3	7	20	9	2	7	18		70
W208	0	1	0	6	7	7	9	7	1	38
Total	4	12	23	68	32	15	87	63	6	310
	Percent of Total Fractures > 0.03 in. by Lithology within Wells									
	Cnglom	VCrsSS	CrsSS	MedSS	FineSS	VFineSS	SiltSt	MudStone	ClayStone	
W201		11.11	11.11	22.22	11.11	0.00	11.11	33.33		
W202			16.67	33.33	4.17	0.00	41.67	4.17		
W203		0.00	0.00	55.56	0.00	0.00	44.44	0.00		
W204		0.00	19.05	23.81	9.52	9.52	38.10	0.00		
W205	0.00	5.08	5.08	15.25	10.17	1.69	45.76	15.25	1.69	
W206	0.00	4.23	4.23	15.49	7.04	4.23	28.17	30.99	5.63	
W207	5.71	4.29	10.00	28.57	12.86	2.86	10.00	25.71		
W208	0.00	2.63	0.00	15.79	18.42	18.42	23.68	18.42	2.63	

greater number of fractures in siltstones near the faults may be due to a higher proportion of siltstone in these wells than in the western wells (Table 3), rather than a greater fracture intensity in siltstones near the faults.

Two series of questions have been formulated to specifically address fracture variability and hydrophysical anomalies among the wells. The first series of questions focuses on the fracturing itself. The correlation between hydrophysical anomaly strength and the number of fractures and their closeness to the anomaly indicates that the existence of multiple fractures could mean the presence of a strong hydrophysical anomaly.

If fractures are correlated with hydrophysical anomalies, then it is important to determine how fractures vary throughout the site, and what factors influence variations in fracture intensity. Tables 6 through 9 address the following four questions regarding fracture intensity and whether it varies among the wells or lithologic groups:

1. Are fractures distributed uniformly within all logged lithologic layers? If this is true, then it may imply that fracturing is relatively independent of lithological controls or structural position.
2. Are fractures distributed uniformly within each lithological layer in each well? If so, then fracture intensity may be controlled by lithology, and be relatively unaffected by structural position.
3. Are fractures with an aperture of >0.03 in. (0.76 cm) distributed uniformly within all lithologic layers? This question is similar to the first, except the emphasis here is on fractures with the largest geometric apertures. Such fractures may represent only a small subset of the most conductive fractures in a well, which may account for most of the flow.
4. Are fractures with an aperture of >0.03 in. distributed uniformly within each lithological layer within each well? This question is similar to the second, except it focuses on the fractures with the largest geometric apertures, which might in turn represent the most conductive fractures.

Table 6 shows that the p-value (the probability of observing the calculated Chi-Square statistic given that the null hypothesis is true) is essentially 0.0, implying that fracture intensity is not uniform among the wells. Wells W204, W205, and W208 are the most anomalous in terms of fracture intensity, as shown by their high Chi-Square values. Table 7 demonstrates that the frequency of fracture variation from well to well is influenced by lithology. The high Chi-Square value for siltstone and mudstone in well W205 shows that the fracture frequency is anomalous in these fine-grained lithologies in the well. The higher values for the coarser-grained layers in wells W202 and W203 confirm that fracturing is anomalous in these units. The p-values show that fracture intensity varies with lithology within individual wells. Tables 8 and 9 show similar results for fractures with apertures greater than 0.03 in. In summary, these tables indicate that fracture intensity varies among wells, and this variation is due not only to differences in the proportion of different lithologies. For example, siltstones in well W205 have a different frequency than siltstones in well W202.

With regards to the hydrophysical anomalies themselves, several questions arise:

1. Does the strength of the conductivity anomaly or number of anomalies vary by well?
2. Does the strength of an anomaly depend upon being located in a particular lithology?
3. Is the strength of an anomaly influenced by the thickness of the unit in which it occurs?
4. Is the strength of an anomaly influenced by the

Table 6. Evaluation of the degree to which fractures are distributed uniformly among the wells, using Chi Square criteria.

Well	Total Thickness of Layer (inches)	Total No. of Fractures	Expected No. of Fractures	Chi Square	p-value
W201	854.54	85	55.8	15.24	
W202	1948.43	92	127.3	9.79	
W203	1086.74	53	71.0	4.57	
W204	722.19	101	47.2	61.37	
W205	7131.56	592	466.0	34.09	
W206	4248.88	269	277.6	0.27	
W207	4821.84	263	315.0	8.60	
W208	5480.03	263	358.1	25.23	
Total	26294.21	1718	1718.0	159.16	4.82E-31

proximity to a contact with another lithologic unit?

5. Is the strength of an anomaly correlated to a sharp contrast in the lithologies of units immediately above and below the unit?

Figure 4 shows the percent of hydrophysical anomalies by lithology within each well. There is insufficient information to carry out meaningful contingency table analyses on these data, but the figure clearly illustrates that the anomalies occur in different lithologies in a manner that is not in proportion to the relative net thickness of the lithologic layers in the wells

Figure 5 illustrates the relation of the thickness of a unit containing a hydrophysical anomaly to the thickness of all units found in the eight wells. There is no obvious visual difference.

The hypothesis that lithologic contrasts are related to anomalies was tested by comparing the anomaly strength to:

1. The absolute strength of the contrast (parameter ATC).
2. The contrast with the nearest adjacent lithology (parameter C_NEAR).
3. The distance to the nearest adjacent lithology.
4. Whether anomalies are predisposed to occur more closely to lithologic unit contacts.

Figure 6 shows the relation between both total contrast (TC) and ATC with the strength of the anomaly. The figure illustrates that there is a weak trend between increasing ATC and anomaly strength, but none between TC and anomaly strength. Figure 6 also compares anomaly strength to the contrast of the unit above (ALCA) and the unit below (ALCB). There is no obvious visual trend between these parameters and anomaly strength.

In addition, Figure 6 shows two parameters relating the anomaly strength to the contrast between the unit containing the anomaly (C_NEAR) and the distance to the nearest adjacent unit (CMIN). These data suggest no obvious trend.

The data shown in Figure 6 were tested to determine if hydrogeologic anomalies tend to be within 1 ft of the nearest contact. Does this imply that hydrophysical anomalies tend to occur close to lithology changes? This proposition was tested by selecting a random point in each unit penetrated by the eight wells and then computing the distance to the nearest contact. Figure 7 summarizes the result. Visually these two distributions appear very similar. A Chi-Square test does not reject this hypothesis, showing with an approximate 86% significance that these distributions are the same. This implies that anomalies do not appear to be preferentially located near major changes in lithology, although lithology contrasts have some importance.

The location and relative strength of each hydrophysical anomaly identified in the eight boreholes are indicated in Figure 2 by a line on the left-hand side of the borehole log. The length denotes the log of the flow rate. The figure indicates that the strongest hydrophysical anomalies are in W205, which intersects the fault.

Table 7. Evaluation of the degree to which fractures are distributed uniformly with lithologic layer in individual wells.

Expected Number of Fractures											
Well No.	1 Cnglom	2 VCrsSS	3 CrsSS	4 MedSS	5 FineSS	6 VFineSS	7 SiltSt	8 MudStone	9 ClayStone	Total	
W201		5.00	14.60	21.71	10.77	7.40	17.62	7.90		85	
W202			8.91	20.40	19.87	9.87	25.99	6.95		92	
W203		3.55	8.58	17.13	0.46	1.67	17.28	4.33		53	
W204		0.62	16.42	15.01	8.87	10.35	45.65	4.08		101	
W205	2.55	18.33	39.77	115.26	48.99	24.87	282.56	53.79	5.88	592	
W206	4.20	11.82	19.29	57.78	30.66	38.73	81.42	22.15	2.95	269	
W207	14.55	10.59	19.06	44.41	23.67	29.78	98.96	21.96		263	
W208	5.28	3.23	9.11	22.75	87.46	36.47	76.03	20.59	2.08	263	
Total	26.59	53.13	135.73	314.47	230.75	159.14	645.52	141.76	10.91	1718	
Chi-Square Analysis											
	Cnglom	VCrsSS	CrsSS	MedSS	FineSS	VFineSS	SiltSt	MudStone	ClayStone	Total	p-Value
W201		0.80	5.06	4.87	3.09	2.62	0.15	8.30		24.90	0.00036
W202			19.23	4.52	5.94	6.28	1.88	1.34		39.19	2.18E-07
W203		1.83	2.45	20.78	0.46	0.27	3.07	2.56		31.41	0.00002
W204		0.62	0.01	1.06	0.51	3.08	1.64	1.06		7.98	0.23973
W205	0 08	17.05	7.47	0.66	2.48	0.33	22.40	14.79	0.13	65.39	4.05E-11
W206	1.15	0.28	1.15	0.25	4.44	12.19	0.00	45.77	5.57	70.81	3.39E-12
W207	0.17	0.55	3.31	10.49	4.51	8.36	19.53	16.51		63.42	3.13E-11
W208	0 02	0.02	0.49	8.92	19.65	0.34	0.65	24.40	57.48	111.96	1.51E-20

2.3 *Multiple Regressions*

A series of step-wise multiple regressions was carried out using a data-mining application, SAS™. The results are summarized in Table 10. This table contains the results for the six multiple regressions with the highest R-square value for different numbers of independent variables.

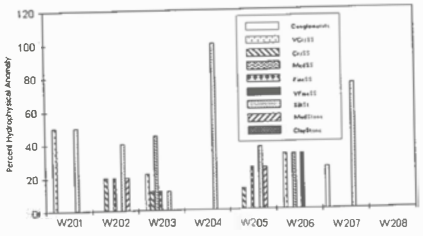

Figure 4. Percent of hydrophysical anomalies by lithology for individual wells. The height of the bars represents the percent of the logged interval of the well comprised by each lithology. Missing bars indicate the absence of a particular lithology in a well.

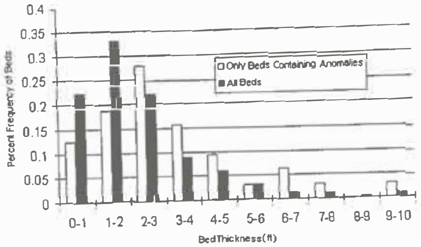

Figure 5. Bed thickness histograms. Open bars represent the histogram of bed thickness for all beds encountered by the wells. Black bars represent the histogram of bed thickness for only those beds containing hydrophysical anomalies. The vertical axis represents the percent of the beds belonging to a particular bed thickness class.

Improvement in R-square decreased significantly after seven variables. Those variables that produced the best R-square values for a given number of parameters are shown in the table and marked by an "X." The table demonstrates that certain variables explain much of the variance in anomaly strength. These variables include the distance to the nearest fractures (D1, D2, D3), the aperture, or width of the fractures (W3), the absolute lithologic contrast (ATC), the dip of the unit below the anomaly (CONDIPB), and the contrast with the unit above (ALCA).

Thus, the multiple regression results suggest that the distances to the three nearest fractures are important, as well as the data on a strong lithology contrast and wider fracture apertures. These variables account for approximately 80% of the variability in anomaly strength.

2.4 *Neural Net Analyses*

All neural net analyses were carried out using NeuroShell II™ Version 3.0 [*Ward,* 1996]. A genetic adaptive GRNN architecture was used [*Specht,* 1991]. GRNNs are designed to predict a continuous variable. They are memory-based feed-forward networks based on the estimation of probability density functions. The classic GRNN contains only one adjustable parameter, termed the *smoothing factor*. The smoothing factor allows the GRNN to interpolate between patterns in the training data set. The genetic adaptive GRNN differs in that it has smoothing factors for each input parameter as well as a conventional overall smoothing factor. These smoothing factors are

Table 8. Fractures > 0.03 in. are distributed uniformly with lithologic layer.

Well	Total Thickness (inches)	Total Fractures	Expected Fractures	Chi Square	p-value
W201	854.54	18	10.1	6.23	
W202	1948.43	24	23.0	0.05	
W203	1086.74	9	12.8	1.13	
W204	722.19	21	8.5	18.31	
W205	7131.56	59	84.1	7.48	
W206	4248.88	71	50.1	8.73	
W207	4821.84	70	56.8	3.04	
W208	5480.03	38	64.6	10.96	
Total	26294.21	310	310.0	55.93	9.75E-10

optimized by iterative changes in the factors based on cross-validation to minimize the mean squared error of the outputs over the entire test set. The genetic adaptive GRNN is much more robust against noisy data and redundant parameters than traditional GRNNs, and is particularly well suited when the input parameters are of different types, and some may have markedly more impact on predicting the output variable than others.

When an observation, which consists of parameter values for all input parameters under consideration, is presented to the GRNN, it is compared to all of the patterns in the training set to determine how closely this observation corresponds to those patterns. The GRNN essentially computes a weighting factor for each training data-set observation, and then computes an overall output value based upon these weights and the input training set parameter values.

Table 9. Evaluation of the degree to which fractures > 0.03 in. are distributed uniformly with lithologic layer in individual wells

<table>
<tr><td colspan="12">All Fractures >,0.03 in. by Lithology within Wells</td></tr>
<tr><td colspan="12">Expected Number of Fractures</td></tr>
<tr><td></td><td>Cnglom</td><td>VCrsSS</td><td>CrsSS</td><td>MedSS</td><td>FineSS</td><td>VFineSS</td><td>SiltSt</td><td>MudStone</td><td>ClayStone</td><td>Total</td><td></td></tr>
<tr><td>W201</td><td></td><td>1.06</td><td>3.09</td><td>4.60</td><td>2.28</td><td>1.57</td><td>3.73</td><td>1.67</td><td></td><td>14.89</td><td></td></tr>
<tr><td>W202</td><td></td><td></td><td>2.32</td><td>5.32</td><td>5.18</td><td>2.58</td><td>6.78</td><td>1.81</td><td></td><td>10.40</td><td></td></tr>
<tr><td>W203</td><td></td><td>0.60</td><td>1.46</td><td>2.91</td><td>0.08</td><td>0.28</td><td>2.93</td><td>0.74</td><td></td><td>5.05</td><td></td></tr>
<tr><td>W204</td><td></td><td>0.13</td><td>3.41</td><td>3.12</td><td>1.84</td><td>2.15</td><td>9.49</td><td>0.85</td><td></td><td>2.47</td><td></td></tr>
<tr><td>W205</td><td>0.25</td><td>1.83</td><td>3.96</td><td>11.49</td><td>4.88</td><td>2.48</td><td>28.16</td><td>5.36</td><td>0.59</td><td>5.73</td><td></td></tr>
<tr><td>W206</td><td>1.11</td><td>3.12</td><td>5.09</td><td>15.25</td><td>8.09</td><td>10.22</td><td>21.49</td><td>5.85</td><td>0.78</td><td>67.51</td><td></td></tr>
<tr><td>W207</td><td>3.87</td><td>2.82</td><td>5.07</td><td>11.82</td><td>6.30</td><td>7.93</td><td>26.34</td><td>5.85</td><td></td><td>51.47</td><td></td></tr>
<tr><td>W208</td><td>0.76</td><td>0.47</td><td>1.32</td><td>3.29</td><td>12.64</td><td>5.27</td><td>10.99</td><td>2.97</td><td>0.30</td><td>15.45</td><td></td></tr>
<tr><td>Total</td><td>6.00</td><td>10.02</td><td>25.73</td><td>57.80</td><td>41.30</td><td>32.48</td><td>109.91</td><td>25.10</td><td>1.66</td><td>172.96</td><td></td></tr>
<tr><td colspan="12">Chi-Square Analysis</td></tr>
<tr><td></td><td>Cnglom</td><td>VCrsSS</td><td>CrsSS</td><td>MedSS</td><td>FineSS</td><td>VFineSS</td><td>SiltSt</td><td>MudStone</td><td>ClayStone</td><td>Total</td><td>p-Value</td></tr>
<tr><td>W201</td><td></td><td>0.84</td><td>0.39</td><td>0.08</td><td>0.03</td><td>1.57</td><td>0.80</td><td>11.19</td><td></td><td>14.89</td><td>0.02111</td></tr>
<tr><td>W202</td><td></td><td></td><td>1.21</td><td>1.35</td><td>3.38</td><td>2.58</td><td>1.53</td><td>0.37</td><td></td><td>10.40</td><td>6.47E-02</td></tr>
<tr><td>W203</td><td></td><td>0.60</td><td>1.46</td><td>1.50</td><td>0.08</td><td>0.28</td><td>0.39</td><td>0.74</td><td></td><td>5.05</td><td>0.53790</td></tr>
<tr><td>W204</td><td></td><td>0.13</td><td>0.10</td><td>1.13</td><td>0.01</td><td>0.01</td><td>0.23</td><td>0.85</td><td></td><td>2.47</td><td>0.87224</td></tr>
<tr><td>W205</td><td>0.25</td><td>0.75</td><td>0.23</td><td>0.54</td><td>0.26</td><td>0.88</td><td>0.05</td><td>2.47</td><td>0 29</td><td>5.73</td><td>6.78E-01</td></tr>
<tr><td>W206</td><td>1.11</td><td>0.00</td><td>0.86</td><td>1.18</td><td>1.18</td><td>5.10</td><td>0.10</td><td>44.62</td><td>13.35</td><td>67.51</td><td>1.54E-11</td></tr>
<tr><td>W207</td><td>0.00</td><td>0.01</td><td>0.73</td><td>5.66</td><td>1.16</td><td>4.43</td><td>14.20</td><td>25.28</td><td></td><td>51.47</td><td>7.42E-09</td></tr>
<tr><td>W208</td><td>0.76</td><td>0.61</td><td>1.32</td><td>2.24</td><td>2.51</td><td>0.57</td><td>0.36</td><td>5.45</td><td>1.63</td><td>15.45</td><td>5.10E-02</td></tr>
</table>

Application of a neural net to the hydrophysical anomaly dataset would be improved if the data set were larger. This is because a small training set and a small test set increase the variability in the results. Also, with a very small training set, it is possible that the training data would not span the *n*-dimensional parameter space and would thereby have difficulty interpolating to new observations with characteristics outside of the data training subspaces. Likewise, it is important to have fewer degrees of freedom (i.e., input variables) in the network than training cases; otherwise, the net "memorizes" the training set without uncovering useful relations.

The performance of a neural net is determined by how well it predicts the strength of the anomaly of a test set as quantified by R and R-square statistics. These statistics vary from 0.0 to 1.0; a perfect prediction has an R and R-square statistic of 1.0. The importance of an input parameter is quantified by its smoothing factor, which can vary from 0.0 (no importance) to 3.0 (very important).

Because of the small (approximately 30) number of hydrophysical anomalies available for use as training and test patterns, the results are sensitive to the random subset selected as the training pattern. For this reason, several random subsets were selected and processed.

Correlation shows up in the smoothing factors as a substitution of one correlated variable in random samples. For example, in one run, the distance to the third nearest fracture might be important. In a subsequent run, this distance might have little importance but the distance to the second nearest fracture would now be important. Highly correlated variables can substitute for one another since virtually all of the information in all of the variables can be contained in any one of the variables.

Neural net regression was much more successful for the logarithm of the anomaly than for the anomaly itself. A series of preliminary neural nets was constructed to look at different components of the data—in particular, fracture-related parameters and lithological parameters. In the preliminary processing that focused on fractures, several parameters played an important role. These included depth of the fractures, width of the fractures, distance from the anomaly to the nearest fractures, and the lithology of the nearest fractures. Depth was probably an artifact of the available dataset, however. Well W205, the deepest well, had the strongest anomalies. The other wells either were not drilled to the depth of W205, or else did not have all of the necessary parameters for the deeper portions of the borehole.

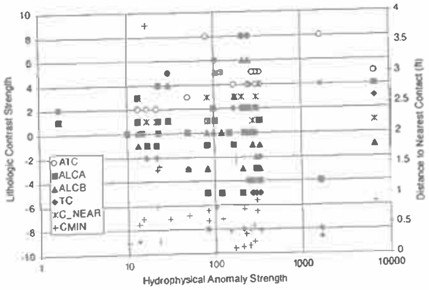

Figure 6. Anomaly strength vs. lithological contrast parameters. The vertical scale on the left-hand side of the graph pertains to the contrast parameters ATC, ALCA, ALCB, TC, and C_NEAR. The vertical scale on the right-hand side indicates the value of the distance parameter CMIN.

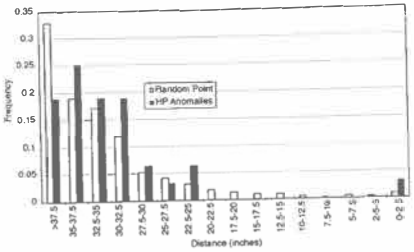

Figure 7. Percent frequency histogram of distance to nearest lithology change. Open bars represent distances between a location randomly assigned in the wells and the nearest contact. Black bars represent the distance from the locations of all hydrophysical anomalies to the nearest contact. The frequencies have been normalized to percentages in order to facilitate visual comparison.

The lithologies above and below the hydrophysical unit did not appear to explain the hydrophysical anomaly. However, the lithologies of the four nearest fractures were quite informative. Although these lithologies correlated very strongly, surprisingly, at least three of them always seemed to have significant smoothing factors. This is reminiscent of the results from the step-wise regression, which showed that the distance to at least three of the four nearest fractures was important. If the information content in any one of these parameters were a good representation of the information content in any other, then it would be expected that only one of the lithology, depth, or aperture parameters would have a significant smoothing factor. The fact that more than one lithology parameter has a significant smoothing factor might be evidence that hydrophysical anomalies are in some way enhanced by the presence of multiple fractures near the anomaly, whether or not these fractures actually have an anomaly associated with them.

These preliminary runs guided the final runs in which redundant variables and depth measures had been eliminated. Tables 11 and 12 summarize those results.

Table 11 shows the mean of the smoothing factors for five randomly drawn training and test sets. The lithology of the fractures (L1 and L2), fracture width (W1 and W2), and proximity (D1 and D2) to fractures to the anomaly are

Table 10. Results of step-wise regression.

No. of Variables	R-square	ALCA	ATC	CDA	CONDIP A	CON DIPB	D1	D2	D3	D4	LCA	LITH	Log(W1)	Log(W2)	Log(W3)	W1	W2	W3
2	0.477	X												X				
2	0.438		X											X				
2	0.419	X															X	
2	0.402							X						X				
2	0.387							X									X	
2	0.383		X														X	
3	0.527	X						X						X				
3	0.513		X			X		X										
3	0.511	X											X	X				
3	0.508	X								X				X				
3	0.507		X					X						X				
3	0.506	X				X								X				
4	0.622						X	X	X									X
4	0.596		X					X	X						X			
4	0.591						X	X	X						X			
4	0.581	X						X	X					X				
4	0.580		X			X	X	X										
4	0.571	X				X							X	X				
5	0.717		X				X	X	X						X			
5	0.711		X				X	X	X									X
5	0.687						X	X	X							X		X
5	0.684						X	X	X					X				X
5	0.679	X					X	X	X									X
5	0.677		X			X	X	X	X									
6	0.802		X			X	X	X	X									X
6	0.783		X			X	X	X	X						X			
6	0.765		X				X	X	X					X				X
6	0.753	X					X	X	X					X				X
6	0.751		X				X	X	X					X	X			
6	0.750		X				X	X	X							X		X
7	0.828		X	X		X	X	X	X									X
7	0.823		X			X	X	X	X					X				X
7	0.820		X			X	X	X	X							X		X
7	0.817		X		X	X	X	X	X									X
7	0.816		X			X	X	X	X		X							X
7	0.815		X			X	X	X	X			X						X

always important. In particular, the distance to the second closest fracture is much more important than the distance to the closest fracture. Two other parameters, used only in the neural net analysis, also were important—UNCONF and ABS(UNCF). These variables were introduced to assess structural or stratigraphic disruption, an area also important in the neural net analyses. Absolute lithology contrast (ATC), lithology of the anomaly (LITH), and distance to the nearest contact (CMIN), have a moderate impact. Bed thickness (BED_TH) and the contrast between the anomaly unit and the nearest adjacent unit (C_NEAR) play very minor roles.

Table 12 shows the R-square and r-square statistics for both the training and test sets. R-square is the coefficient of multiple determination, whereas r-square is the more familiar coefficient of determination [*Ward*, 1996], which is the square of the correlation coefficient. The R-square value for the training sets averages nearly 92%, with a variation of 81% to 100%. The R-square value for the test sets averages nearly 77%, with a variation of 50% to 97%. Note that the lowest R-square for the test set comes from realization 2, which conversely has the highest value (1.0) for the training sets. The smoothing factors for this realization are also somewhat anomalous. The R-square values for both the training and test sets are higher than for the multivariate regression. This suggests that some of the input parameters have a nonlinear relation with anomaly strength. In general, the GRNN achieves about a 20% improvement over the multivariate regression in terms of R-square values.

Table 13 shows the predictions made by the neural net method for the ten test sets of observations. In general, the predictions are reasonably accurate, the average error being 0.0250 and the standardized mean squared error 0.34.

Thus, the neural net analysis confirms the results of the simpler statistical techniques and suggests that a GRNN offers greater accuracy than multivariate regression.

Table 11. Average smoothing factors for neural net analyses.

Average of 5 Realizations	Smoothing Factor [0 to 3.0]
Lithology to 1st Nearest Fracture	2.37
Distance to 2nd Nearest Fracture	2.24
Lithology to 2nd Nearest Fracture	2.09
Aperture of 1st Nearest Fracture	1.97
Absolute Value of Angular Difference between Upper and Lower Contacts	1.86
Difference between Upper and lower Contacts	1.59
Distance to Nearest Contact	1.28
Aperture of 2nd Nearest Fracture	1.21
Absolute Grain Size Contrast	1.15
Grain Size of Unit Containing Anomaly	1.12
Distance to 1st Nearest Fracture	1.08
Minimum Apparent Distance to Nearest Contact	0.76
Bedding Thickness	0.60
Dip of Contact with Unit Above	0.47
Grain Size Contrast with Nearest Unit	0.29

3. CONCLUSIONS

The statistical results for the Wake Co. site support the following conclusions:

1. There are statistically significant correlations between the geologic variables directly measured or derived from core data or borehole imagery and the strength of hydrophysical anomalies.
2. Hydrophysical anomalies do not appear to be located preferentially in particular lithologies for all eight wells. The frequency histograms and associated statistical test results show that hydrophysical anomalies are located in randomly selected subsets of all of the lithologic units.
3. Hydrophysical anomalies are not preferentially located near to boundaries between contrasting lithologic units. Frequency histograms of the proximity of anomalies to the nearest lithologic boundary are statistically indistinguishable from the distance from a random point located in every unit to its nearest boundary.
4. There is a weak trend between the magnitude of a hydrophysical anomaly and the strength of the contrast between the lithologic unit containing the anomaly and the units above and below it.
5. The trend noted in the conclusion above is independent of whether the anomaly occurs in a fine-grained unit surrounded by coarse-grained units or a coarse-grained unit surrounded by fine-grained units.
6. There is no correlation between the strength of the hydrophysical anomaly and the strength of the contrast with the lithologic unit above or below.
7. There is no correlation between the strength of the hydrophysical anomaly and the distance to either the upper or lower contact with the adjacent lithologic units.
8. The strongest hydrophysical anomalies occur in the fine-grained lithologies in Well W205, which intersected the fault and was drilled and logged deeper than most of the other wells. The anomalies in well W205 have three unique characteristics: they occur preferentially in siltstone or mudstone lithologies,

Table 12. Statistics for GRNN prediction of hydrophysical anomaly strength.

Training Set	#1	#2	#3	#4	#5	Average
R squared	0.91	1.00	0.99	0.81	0.88	0.92
r squared	0.94	1.00	0.99	0.90	0.88	0.94
Mean squared error	0.05	0.00	0.01	0.12	0.06	0.05
Mean absolute error	0.15	0.00	0.06	0.24	0.07	0.10
Min. Absolute error	0.00	0.00	0.00	0.00	0.00	0.00
Max. Absolute error	0.80	0.00	0.25	1.04	1.35	0.69
Correlation coefficient r	0.97	1.00	0.99	0.95	0.94	0.97
Percent within 5%	45.46%	100.00%	77.27%	27.27%	87.50%	67.50%
Percent within 5% to 10%	36.36%	0.00%	13.64%	22.73%	3.13%	15.17%
Percent within 10% to 20%	13.64%	0.00%	9.09%	31.82%	6.25%	12.16%
Percent within 20% to 30%	0.00%	0.00%	0.00%	9.09%	0.00%	1.82%
Percent over 30%	4.55%	0.00%	0.00%	9.09%	3.13%	3.35%
Test Set	**#1**	**#2**	**#3**	**#4**	**#5**	**Average**
R squared	0.86	0.50	0.97	0.85	0.67	0.77
r squared	0.96	0.53	0.98	0.87	0.73	0.81
Mean squared error	0.04	0.34	0.01	0.02	0.19	0.12
Mean absolute error	0.15	0.29	0.08	0.11	0.20	0.17
Min. Absolute error	0.00	0.00	0.00	0.03	0.00	0.01
Max. Absolute error	0.37	1.70	0.14	0.36	1.35	0.78
Correlation coefficient r	0.98	0.73	0.99	0.93	0.85	0.90
Percent within 5%	50.00%	60.00%	50.00%	80.00%	60.00%	60.00%
Percent within 5% to 10%	10.00%	0.00%	40.00%	0.00%	10.00%	12.00%
Percent within 10% to 20%	10.00%	30.00%	10.00%	10.00%	20.00%	16.00%
Percent within 20% to 30%	20.00%	0.00%	0.00%	0.00%	0.00%	4.00%
Percent over 30%	10.00%	10.00%	0.00%	10.00%	10.00%	8.00%

which is not true for anomalies in other wells; they occur at a greater depth than in the other wells; and the fractures nearest the anomalies have greater apertures than the fractures near anomalies in other wells. The depth correlation is probably an artifact.

9. Away from faults, hydrophysical anomalies are smaller on average and not as strongly associated with siltstone and mudstone. Near faults in the hanging wall, the strength of the anomalies is greater and they are correlated with fractures with larger aperture.
10. The results of our analyses confirm that a fault-related deformation produces new fractures or enhances the aperture of existing fractures in lithological units with lower resistance to shear—mudstones and siltstones—and thereby increases the strength of hydrophysical anomalies.

4. RECOMMENDATIONS

This section offers recommendations for using the results of this study to construct site-scale DFN and SC flow models. The results confirm that it is not correct to assign permeability values to grid cells or flow properties to fractures based on lithologic type alone. The boundaries between contrasting lithologic types do not focus strain. If they did, then the DFN model could have reproduced this effect by having large, bedding-parallel fractures at these interfaces with enhanced transmissivity values. SC models could have approximated this effect by having bedding-parallel layers of grid cells with enhanced subhorizontal permeability. While there is some correlation between lithological contrasts, the correlation is second order and should probably be ignored in preliminary flow models.

Table 13. Comparison of measured hydrophysical anomaly strength with strength predicted by GRNN for ten randomly selected anomalies not used in the GRNN calibration.[a]

#1		#2		#3		#4		#5	
Actual	GRNN	Actual	GRNN	Actual	GRNN	Actual	GRNN	Actual	GRNN
2.52	2.52	3.22	2.62	2.44	2.46	2.52	2.48	3.82	2.48
2.48	2.45	2.52	2.52	2.34	2.29	2.48	2.54	2.52	2.52
2.48	2.39	2.52	2.44	2.32	2.41	2.40	2.35	2.48	2.44
2.22	2.19	2.22	1.92	2.18	2.17	2.35	2.10	2.45	2.39
2.09	2.28	2.09	2.09	1.92	2.03	2.34	2.27	2.40	2.22
2.02	1.99	1.48	1.46	1.48	1.60	2.32	2.43	2.09	2.35
1.99	2.23	1.37	1.37	1.37	1.28	2.18	2.21	1.48	1.47
1.48	1.78	1.34	1.34	1.37	1.32	2.02	1.99	1.37	1.37
1.12	1.37	1.18	1.34	1.12	1.26	1.92	1.83	1.34	1.34
1.00	1.37	0.22	1.92	1.12	1.21	1.12	1.49	1.18	1.34

[a] The ten rows, corresponding to the randomly selected anomalies for each of the five test sets, were sorted by anomaly, from largest anomaly to smallest, to illustrate that the GRNN tends to overpredict the strength of small anomalies (calculations were carried out for five runs).

Fault proximity is a first-order control in and of itself, and lithology plays a significant role near faults. Deformation is greatest in the hanging-wall siltstones and mudstones within the deformation zone that extends from the fault eastward to the fold hinge that intersects the bottom of W204. This implies that fractures in these lithologies and structural positions should have larger aperatures, resulting in higher transmissivity. Alternatively, the grid cells within this region of a SC model would have higher layer-parallel permeability. Based on the data obtained, the footwall appears to be similar to the rock outside of the hanging-wall deformation zone.

The fact that anomalies do exist outside of the hanging-wall zone, but are smaller and not as strongly correlated with lithology, suggests simple "background" fracture and permeability models for the remainder of the rock mass. At least for the preliminary model, the background fracturing would be homogeneous throughout the model. This means that the discrete fractures in the DFN model would be distributed with the same size and orientation distributions, the same transmissivity and transport properties, and the same average intensity independent of depth, lithology, or location. In the SC model, the permeability, porosity, and transport parameter values would be assigned as random (Monte Carlo) draws from a single parent distribution for each parameter. Only in the vicinity of the hanging-wall deformation zone would properties be changed as previously described.

The next stage in refining these DFN or SC models would be to simulate field flow or transport experiments in order to assess whether the models are reproducing the first-order effects, and if so, whether certain second-order effects should be included to improve the modeling forecasts. There is considerable freedom in assigning transmissivity and transport properties either to the fractures themselves in the DFN formulation or as effective properties to the stochastic continuum models. Iterative refinement of these properties to match the field-flow or transport results is usually an important step in the evolution of models that will be used subsequently for forecast or design.

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DOCUMENT

3

FOSSIL FUELS

Coals

Coals are classified as ***humic coals*** if they are *derived from humic substances via a pe* *stage* and as ***sapropelic coals*** if they are *formed from fairly fine-grained organic mud* *quiet, oxygen-deficient shallow waters.* The humic coals are lustrous, dark-brown to black, exhibit stratification, and often contain the remains of woody tissue. The sapropelic coals are dull, unstratified, and contain allochthonous organic and mineral matter. The sapropelic coals are subdivided into cannel and boghead coals. The conversion of organic matter to coal involves two stages: biochemical and geochemical. The biochemical phase involves biological processes; the geochemical stage involves physicochemical processes due to increasing pressure and temperature. These processes lead to a release of volatiles, primarily methane, water, and carbon dioxide; the elimination of oxygen-containing functional groups; and an increase in the percent of aromatic units. These changes are illustrated in Figure 5–27, which shows the relative increase in carbon with increasing degree of coalification.

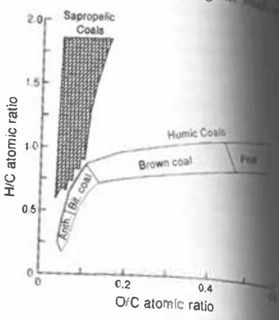

Figure 5–27
van Krevelen (1963) diagram indicating the changes in hydrogen, oxygen, and carbon content during the coalification process. After Killops and Killops (1993).

Of major environmental interest is the metal, sulfur, and fly ash content of coals. Metals that were incorporated in the original organic material tend to remain during the coalification process. Thus, coal is often high in a number of trace elements of environmental concern. Lyons et al. (1989) determined the concentrations of trace elements in a variety of coals, ranging from high-volatile bituminous coals to meta-anthracites. Concentration ranges determined for elements of environmental interest are given in Table 5–6.

Lyons et al. (1989) also investigated the distribution of these trace elements between organic and inorganic (i.e., mineral) components of the coal. For the elements listed in Table 5–6, they concluded that As, Co, Cu, Ni, Sc, and Th generally showed an inorganic association, whereas Cr, Sb, U, V, W, and Zn generally showed an organic association. Se and Pb did not correlate with either association. Metals associated with inorganic components would presumably remain with the fly ash and could be successfully removed from the effluent stream by electrostatic precipitation of the fly ash. Metals associated with organic components would be released to the effluent stream during combustion and dispersed into the atmosphere. These associations would be expected to vary on a coal-by-coal basis, so it is necessary to determine the distribution of elements in a particular coal in order to determine the potential trace metal contribution of this coal to the atmosphere during combustion (see Case Study 5–4).

Table 5–6 Concentration Ranges in Coal for Some Elements of Environmental Interest*

Element	Concentration range (ppm)	Element	Concentration range (ppm)
Sc	0.6–10.3	As	0.7–31
V	6–109	Se	0.4–3.3
Cr	2.6–25.4	Sb	0.1–7.3
Co	1.1–24.1	W	0.2–1.3
Ni	2–50	Pb	3–20
Cu	6–54	Th	0.5–3.7
Zn	3–65	U	0.2–3.8

*From Lyons et al. (1989).

CASE STUDY 5–4
Distribution of Metals and Other Elements in Coals

A number of studies have been carried out on the distribution of metals and other elements in coal. Several of these are cited in this case study to indicate the variability of these elemental associations in coal. Christanis et al. (1998) found that in the Philippi peat of eastern Macedonia, Greece, Ge, Mo, Pb, Se, Ta, Tl, U, and W were correlated with organic content and the other trace elements were correlated with mineral phases. For lignites from central Anatolia, Turkey, Querol et al. (1997) found that Mn, B, Be, Ge, Y, Zr, Nb, Hf, W, and U showed positive correlation with organic matter and Mn, U, Th, Sc, Ge, and HREE showed positive correlation with phosphate, suggesting that apatite or another phosphate mineral is the major host. Co, Mo, Ta, Pb, and IREE showed positive correlation with both Fe and S, indicating that Fe-sulfide minerals are the hosts for these elements. As and V had mixed affinities. For United Kingdom coal fields, Spears and Zheng (1999) found that Rb, Cr, Th, Ce, Zr, Y, Ga, La, Ta, Nb, and V were associated with the clay minerals; As, Mo, Sb, Tl, Se, Bi, and Pb with pyrite; Sr and Ba with phosphate minerals. Germanium was the only element that had a major organic association. For medium- to high-volatile bituminous coals from Nova Scotia, Canada, Mukhopadhyay et al. (1998) found that most lithophile elements, including B, Cr, U, V, and the REE, were associated with the clay minerals; Cu, Pb, and Zn with the sulfide minerals; and Cl, Ca, As, and Mn with organic matter. Of note is the marked variability of the element associations. Major factors affecting trace element concentrations are the abundance and sources of detrital minerals, the presence of volcanic material, and seawater or brine incursions into the basins of deposition.

Sulfur occurs in coal either combined with organic molecules or as physically separate sulfide minerals (of which pyrite is the most common). Sulfur occurs in reduced form (S^-, S^{2-}) because the organic-rich depositional environment is reducing (see Chapter 4). If Fe^{2+} (or other metal ions) is present, it will combine with the reduced sulfur to produce minerals such as marcasite (FeS) and pyrite (FeS_2). If there is a low abundance of metal ions, free hydrogen sulfide (H_2S) and polysulfides (HS_4^-, HS_5^-, S_4^{2-}, S_5^{2-}) are formed. These species can combine with various organic molecules to form a variety of sulfur-containing compounds. In terms of "cleaning up" coal, the way in which sulfur occurs in the coal is of key importance. If the sulfur occurs in separate sulfide minerals, then in principle it can be physically separated by flotation techniques. If the sulfur is bound to organic molecules, there is no effective way to remove the sulfur before burning the coal.

Petroleum

Petroleum *is any hydrocarbon-rich fluid (liquid or gas) derived from kerogen by increases in pressure and temperature.* ***Kerogen*** *is a polymeric organic material that occurs in sedimentary rocks in the form of finely disseminated organic macerals (the preserved remains of plant material).* Four types of kerogen (I, II, III, and IV) have been distinguished on the basis of H/C and O/C atomic ratios, types of organic molecules (aliphatics versus aromatics), functional groups, and other criteria. Type II kerogen is the most common precursor for petroleum. Type I has the highest petroleum-forming potential but is present in low abundance. Type IV kerogen is not a petroleum precursor. Kerogen is converted to petroleum through a series of reactions starting in the ***diagenetic environment*** *(the environment in which processes occur at pressures and temperatures greater than those of the weathering environment but below those required to produce metamorphism)* and ending at temperatures of about 225°C. These reactions result in the expulsion of CO_2 and CH_4 and a reduction in the size of the hydrocarbon molecules. The hydrocarbon formation process for a typical source rock is schematically illustrated in Figure 5–28 (p. 148). Note that natural gas is generated throughout the P–T range, but the formation of oil is confined to a narrow P–T range. Thus, the thermal history of a basin is an important factor in terms of its oil-producing capability. Also note the reduction in the size of the mean hydrocarbon molecule with increasing temperature.

Graphical Representations of Water Chemistry Two types of diagrams are commonly used to portray water chemistry, Stiff and Piper. Stiff diagrams show the concentrations (in milliequivalents) of the major ions (both cations and anions) as a shape that gives both the relative abundance of the various species and the total abundance. Piper diagrams are trilinear representations of cation, anion, and combined cation and anion proportions. Piper diagrams are often used to classify water types. The following two examples illustrate the plotting of Stiff and Piper diagrams.

EXAMPLE 9–1 In this example we will plot the chemical data for the Columbia and Rio Grande rivers and the Pennsylvania groundwater (Table 9–7) on a Stiff diagram. The following table illustrates the calculation for the Columbia River water. We start by determining the concentration of each ion in millimoles per liter and then calculate the concentration of each ion in milliequivalents. The concentrations in milliequivalents are plotted on the Stiff diagram, as shown in Figure 9–5, and the various points are connected by straight lines. Note that the concentrations of the Na^+ and K^+ ions have been combined.

Columbia River

	Ca^{2+}	Mg^{2+}	Na^+	K^+	Cl^-	SO_4^{2-}	HCO_3^-
mg L^{-1}	19	5.1	6.2	1.6	3.5	17.1	76
mmol L^{-1}	0.47	0.21	0.27	0.04	0.1	0.18	1.25
meq L^{-1}	0.95	0.42	0.27	0.04	0.1	0.36	1.25

The shape of the field is a representation of the relative proportions of the various ions, and the size of the field represents the total ionic concentration. The Rio Grande river and Central Pennsylvania ground waters are also plotted in Figure 9–5. From the shape of the Stiff diagrams we can easily infer that the Rio Grande has a much greater concentration of all ionic species than the Columbia River and that the bicarbonate ion, relative to the sulfate ion, is much less important in the Rio Grande than it is in the Columbia River. Inspection of the Central Pennsylvania groundwater diagram reveals that the dominant cation is Ca^{2+} and the dominant anion is HCO_3^-, so this is a Ca-carbonate water. Stiff diagrams are particularly useful when plotted on a map because they give a graphical representation of regional variations in water chemistry.

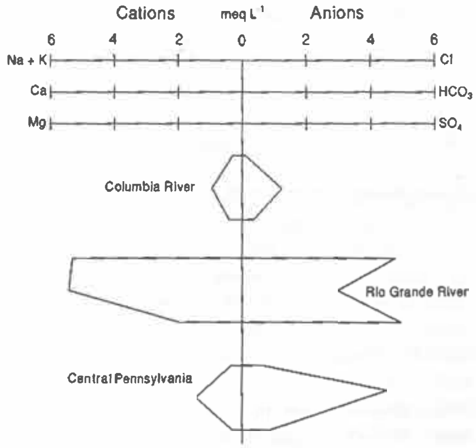

Figure 9–5
Stiff diagram for Columbia and Rio Grande river waters and Central Pennsylvania groundwater. See text for discussion.

■

EXAMPLE 9–2 In this example we plot the Columbia River data from Example 9–1 on a Piper diagram. As in Example 9–1, we start by calculating the concentration of each ion in milliequivalents. We now normalize the cations and the anions to 100% (as shown in the following table) so that we can plot them on the Piper diagram.

Cation concentrations			Anion concentrations		
	meq L^{-1}	Normalized		meq L^{-1}	Normalized
Ca^{2+}	0.95	56.5	Cl^-	0.10	5.8
Mg^{2+}	0.42	25.0	SO_4^{2-}	0.36	21.1
$Na^+ + K^+$	0.31	18.5	HCO_3	1.25	73.1
Total	1.68	100.0		1.71	100.0

The normalized cation and anion concentrations are plotted in their appropriate triangle (Figure 9–6). The data plotted on each triangle are then projected into the quadrilateral by drawing a line from the point on the cation triangle parallel to the Mg axis into the quadrilateral and by drawing a line from the point in the anion triangle parallel to the SO_4 axis into the quadrilateral. The intersection of these two lines marks the location of the point to be plotted on the quadrilateral (Figure 9–6). Symbols of different size are sometimes used to indicate differences in total dissolved species. This convention is used in the example. The data for the Rio Grande river and the Central Pennsylvania ground waters are also plotted in Figure 9–6. ■

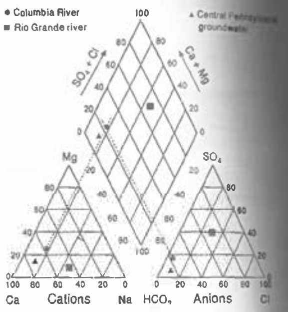

Figure 9–6
Piper diagram for Columbia and Rio Grande river waters and Central Pennsylvania groundwater. See text for discussion.

Piper diagrams have two main uses. The first is the graphical representation of water chemistry for the purpose of water classification (see the next section). The second is to determine if a series of water compositions represent the mixing of two end members. If the samples are the result of two-end-member mixing, they will plot along straight lines in each of the fields of the diagram. If they do not plot along straight lines, then their compositions are not controlled by simple two-end-member mixing (Case Study 9–2).

Hydrofacies Back (1966) divided the ion triangles of the Piper diagram into various fields that correspond to water type or *chemical facies* (Figure 9–7). This is a convenient way to classify water types on the basis of their major ion chemistry. Examples of chemical facies names are calcium bicarbonate and sodium chloride. If the water plots in the center of an ion triangle, it is referred to as *mixed-cation* or *mixed-anion facies*. With reference to the waters plotted in Figure 9–6, the Columbia River water belongs to the calcium-bicarbonate facies, the Rio Grande river water to the mixed-cation–mixed anion facies, and the Central Pennsylvania groundwater to the calcium-bicarbonate facies. The hydrochemical facies in which the water sample plots potentially reveals information about the factors controlling the water chemistry. For example, the observation that the Columbia River water plots in the calcium-bicarbonate facies suggests that rock weathering is the major factor controlling water chemistry (see next section). The observation that the Central Pennsylvania groundwater plots in the calcium-bicarbonate facies suggests that dissolution of limestone, which would provide the Ca and bicarbonate ions, is important

CASE STUDY 9–2
Mixing of Acid Mine Drainage and Lake Water

In Case Study 2–1, Foos (1997) investigated the mixing of acid mine drainage from an abandoned coal mine with water discharged from a lake. The chemical compositions of the acid mine drainage, lake water, and the stream water downstream from the point of mixing were plotted on a Piper diagram (Figure 9–C2–1). This plot indicated that simple mixing would explain the concentrations of the major ions in the stream (mixed water). Further testing of the mixing model revealed that Ca^{2+}, Mg^{2+}, Na^+, K^+, and Cl^- concentrations could be explained by simple mixing, but not HCO_3^- and SO_4^{2-} concentrations. For HCO_3^- and SO_4^{2-}, the deviation from simple mixing was about 14%, so as a first approximation simple mixing is a reasonable assumption. The deviations from simple mixing for Fe^{2+} (1800%) and Mn^{2+} (39%) were significant. The reasons for the nonconservative behavior of these two species was discussed in Case Study 2–1. In this study, the Piper diagram was used to make an initial evaluation of the conservative versus nonconservative behavior of various species in solution.

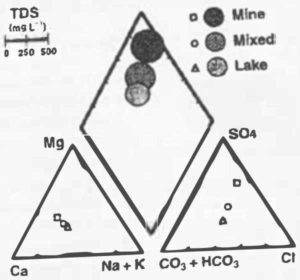

Figure 9–C2–1
Piper diagram showing the compositions of the mine and lake discharges and the mixed stream water. From Foos (1997).

Source: Foos (1997).

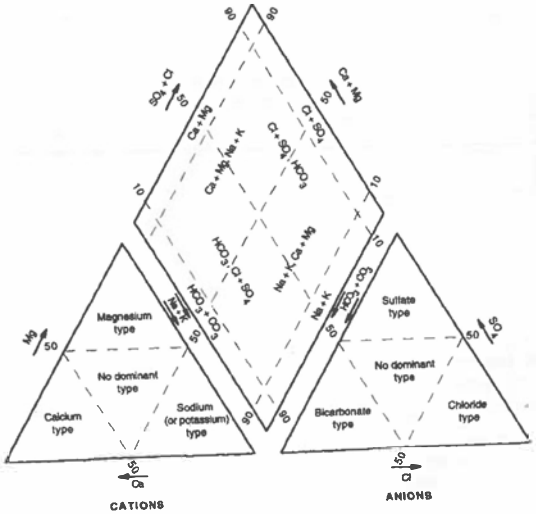

Figure 9–7
Hydrochemical facies. After Back (1966).

CASE STUDY 9–7

Sulfide Mine Tailings at Two Sites in New Mexico, U.S.A.

Boulet and Larocque (1998) investigated the characteristics of two sulfide mine tailings sites. For both deposits the common ore minerals were chalcopyrite, sphalerite, and galena. At one site (CPA) the tailings were deposited in a polyethylene-lined bermed impoundment. Mining at this site ended in 1995. At the other site (CM) the tailings were deposited in a valley at the headwaters of an ephemeral stream. Mining ceased at this site in 1950.

At the CPA site the dominant tailings minerals are calcite, quartz, and pyrite. A lime slurry was added to the tailings before they were discharged to the tailings pond. The tailings pond water is alkaline (pH = 7 to 8.3) and mineralogical investigation showed no evidence of dissolution of the primary calcite, indicating that the added lime slurry is still providing sufficient buffering capacity. Under the present conditions, the metals in the CPA tailings are immobile and acid drainage is not a problem at this site.

At the CMT site significant weathering and oxidation has occurred. Besides the sulfide minerals, the other primary minerals in this tailing pile were quartz, calcite, and several other silicate minerals. Because of weathering and oxidation, the current assemblage of primary minerals are quartz and the sulfide minerals pyrite, sphalerite, and chalcopyrite. Essentially all the primary calcite has been consumed in buffering reactions. Water draining from the site is strongly acidic (pH = 2.3) and has high metal concentrations. There has been a significant redistribution of metals within the tailings pile. Abundant secondary minerals (the result of the weathering of the primary minerals) have formed throughout the tailings pile. These secondary minerals consist of various iron oxides, hydroxides, and sulfates plus gypsum. In places, these secondary minerals have cemented the tailings to form *hardpans*. The hardpan represents a local zone of neutralization and precipitation, and the highest metal concentrations are found in the hardpan. Elements such as Ag, Au, Pb, and Sb were found at highest concentrations in the layer above the hardpan. These elements form highly insoluble complexes with sulfate, and the slight increase in pH as the waters percolated down through the tailings pile was sufficient to lead to the precipitation of the metal sulfates. The trapping of metals (Ag, Au, As, Pb, and Sb) in the hardpan layers was an important process that inhibited movement of these metals into the local environment. Metals (Cd, Cu, Fe, and Zn) not trapped in the hardpan layers were readily transported by the acid waters draining the site.

Source: Boulet and Larocque (1998).

vironments, such as deltas. Subsequent exposure of this material to subaerial weathering leads to acid drainage and the release of metals. This exposure can be due to either uplift or artificial drainage for land recovery (Case Study 9–8).

Heavy Metals

As defined earlier, heavy metals are those metals of atomic number 20 and greater. Of the heavy metals, the transition elements, As and Se (strictly speaking, metalloids), Cd, Hg, and Pb have attracted the greatest environmental interest. Other metals specifically involved in issues of nuclear waste disposal and radioactive fallout will be considered in the next section.

In a strongly reducing environment, and in the presence of sulfur, all these elements form insoluble sulfides. This, of course, is the reason why coals, which form in strongly reducing environments, contain significant amounts of heavy metals. As long as the environment remains reducing, the elements are immobile and are retained in the sediment. Changes in oxidation–reduction conditions can lead to a release of these elements. For less strongly reducing conditions, or environments that lack sulfur, the heavy metals can become variably mobile. The factors that control element mobility are pH, Eh, and the presence of organic compounds. The most important factors differ depending on the element. Thus, it is convenient to form three metal groups: (1) transition metals, Zn, Cd, and Pb; (2) As and Se; and (3) Hg.

Transition Metals, Zn, Cd, and Pb Under most oxidation–reduction conditions, these elements occur in solution as divalent or trivalent cationic species. Brookins (1988), a very useful reference, gives a number of calculated Eh–pH diagrams for virtually all systems of geochemical interest, and the student should consult this source for Eh–pH diagrams for specific metals. At high pH, many of these elements form insoluble oxyhydroxides or, in the presence of carbonate, insoluble carbonates. As we know from

CASE STUDY 9–8

The Effect of Acid Soil Leaching on Metal Concentrations in Streams

Sulfide-bearing marine and lacustrine sediments are common in the coastal regions of Finland. Artificial drainage of these areas during the past few decades has exposed these sediments to atmospheric O_2 and a high oxidation rate. The result has been the development of acid soils (pH = 2.5 to 5.0). Water-chemistry measurements were made for a stream draining this region under various flow conditions (Åström, 2001). The headwaters originate in an unpopulated area underlain by glacial till, peat, and glaciofluvial deposits. Water-chemistry measurements made at this point constitute the metal baseline concentrations. The concentrations of the metals in the outlet waters (after the stream had traversed the sulfide-bearing sediments) were compared to the baseline values. The outlet-to-baseline ratios varied from 0.3 to 55 as a function of the metal, the magnitude of the stream flow, and the season. The metals that showed downstream depletion were As, Pb, Sb, Ti, and V. The limited leaching of these metals from the acid sulfate soils was believed to be due to low absolute abundances, low concentrations in easily weathered minerals, or low mobility in the soils due to complexation with oxyhydroxides and humic substances. For the elements that showed downstream enrichment, the order, from most enriched to least enriched, was Ni > Co ≈ Cd ≈ Zn > U ≈ Al ≈ Cu ≈ Mn. Åström noted that the downstream variations for all the elements were closely similar to that for SO_4^{2-}, suggesting that the metal and sulfate had a similar hydrogeochemical behavior.

Figure 9–C8–1 shows a typical pH–depth profile for acid sulfate soils and the various redox environments. Seasonal changes in this profile can be directly related to variations in metal release to the stream. Åström proposed the following model to explain the seasonal variations in metal and sulfate concentrations in the stream:

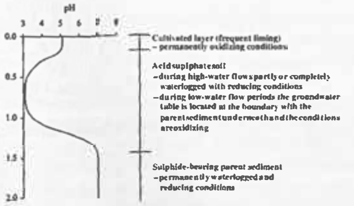

Figure 9–C8–1
pH, redox, and hydrological characteristics of a typical acid sulfate soil. After Åström (2001).

1. During the summer, higher temperatures and a lowered groundwater table favor aerobic bacterial oxidation of sulfide minerals and the release of metals and sulfate to the soils. Substantial alteration of soil minerals also occurs.
2. During periods of heavy rainfall in the autumn, the soluble weathering products are washed from the soils, and sulfate, metal ions, and hydrogen ions are discharged to the stream. As winter approaches, temperatures fall and the water table rises, leading to a cessation in the formation of soluble weathering products.
3. Metal and sulfate inputs to the stream during the early summer are small because most of the soluble weathering products were removed during the fall rains and there has been little formation of new material.
4. Under low flow conditions (summer and early autumn), the contribution from the acid soils is negligible compared to that of the areas covered with the other sediments.

Source: Åström (2001).

earlier discussions, adsorption is an important process. Thus, another important factor is the presence of suitable sorbates, among which are Mn and Fe oxyhydroxides. At low pH, sorbtion is negligible for these metals, but with increasing pH, adsorption becomes an important process (Figure 9–16), effectively removing the metals from solution by adsorption to particles and ultimately to the sediments. These elements also form complexes with dissolved organic matter (humic acids). Tipping and Hurley (1992) determined the following binding order for various metals and humic substances: $Mn^{2+} < Cd^{2+} < Co^{2+} < Ni^{2+} \sim Zn^{2+} < Pb^{2+} < Cu^{2+} < VO^{2+}$.

One notable exception to the behavior just described is vanadium. Under reducing conditions, V occurs as the relatively immobile V^{3+}. In oxic environments, the solubility of V increases dramatically because of conversion to higher oxidation states, V^{4+} and V^{5+}, and the formation of vanadyl cations, $VO_2(OH)_3^{2-}$, H_2VO^{4-}, and HVO_4^{2-}.

Selective Extraction In any given environment, the actual distribution of a metal among various phases may differ substantially from that predicted from first principles. One way to address this question is by a technique known as *selective extraction*, in which various leaching experiments are done to remove the metals from specific phases. The leaching agents are selected so that they remove metals that occur in different ways, i.e., as exchangeable cations, bound to carbonates, bound to amorphous Fe and Mn hydroxides, bound to organic matter and sulfides, and as essential components of soil minerals. The experiment is done in a stepwise fashion, starting with a leaching agent that removes only the least tightly held cations. The last step is often a strong acid leach that breaks down the soil minerals. From these types of experiments, estimates can be made of the mobility of various metals in the specific environment. Case Study 9–9 describes a typical selective extraction experiment.

Arsenic and Selenium Arsenic and selenium differ from the transition metals in that they occur in solution as neutral and negatively charged species. Under oxidizing conditions, arsenic is in the +5 state. Given the range of pH values found for the natural environment, As^{5+} exists in solution as $H_2AsO_4^-$ and $HAsO_4^{2-}$. Under reducing conditions, arsenic is in the +3 state and exists in solution as $H_3AsO_{3\,(aq)}$ and $H_2AsO_3^-$. Selenium also shows multiple oxidation states. Under strongly oxidizing conditions, it is in the +6 state (SeO_4^{2-}), under intermediate oxidizing conditions in the +4 state ($HSeO_3^-$ and SeO_3^{2-}), and under reducing conditions, it occurs in its elemental form or in the −2 state (HSe^-). Under reducing conditions, if sulfur is present, both As and Se are incorporated in sulfide minerals. Because As and Se exist in solution as negatively charged species, adsorption increases with declining pH (the surface becomes less negatively charged or positively charged). The arsenate (+5) species form inner-sphere complexes at the iron oxyhydroxide surface and are strongly adsorbed near neutral pH (note from Table 9–11 that for the oxyhydroxides $pH_{pznpc} = 7.8–8.5$), whereas the arsenite (+3) species are only weakly adsorbed at all pH values. For selenium, the situation is reversed and the selenite (+4) species are strongly adsorbed whereas the selenate (+6) species are weakly adsorbed.

The difference in adsorption behavior for the various species of arsenic and selenium is important in terms of their transport in the surface environment. In the case of arsenic, a strongly oxidizing environment that favors the formation of arsenate species will lead to adsorption by oxyhydroxides and removal from the aqueous environment. If conditions become reducing, the bound arsenate will be converted to arsenite and can be liberated from the particles to the solution. The reverse behavior would be noted for the various selenium species; i.e., selenium tends to remain in solution under oxidizing conditions but is removed under reducing conditions. The important point is that changes in the redox conditions of the environment can lead to either removal or liberation of arsenic and selenium. The other important point is that the kinetics of the redox reactions is slow, so disequilibrium is common. Thus, predicting the mobility of arsenic and selenium under a particular set of environmental conditions is difficult.

CASE STUDY 9–9
Geochemical Behavior and Mobility of Metals in a Sediment Retention Pond

Lee et al. (1997) studied the mobility of metals in a sediment retention pond located along a motorway in France. The purpose of these retention ponds is to accumulate particulates contaminated by heavy metals, thus preventing their discharge to surrounding streams. Eight sediment cores were driven to depths of 16 to 20 cm. The interstitial fluids were extracted and analyzed for their metal content. The metals associated with the solid phases were then analyzed using sequential chemical extraction. The authors used a five-step process, as follows:

1. Fraction I: *Exchangeable*, 1 M $MgCl_2$ at pH 7
2. Fraction II: *Bound to carbonate*, 1 M sodium acetate adjusted to pH 5.0 with acetic acid for 5 h
3. Fraction III: *Bound to amorphous Fe and Mn hydroxides*, 0.04 M hydroxylamine hydrochloric acid in 25% (v/v) acetic acid at 96°C for 6 h
4. Fraction IV: *Bound to organic matter and sulfides*, 30% H_2O_2 and 0.02 M nitric acid at 85°C for 5 h
5. Fraction V: *Residual*, concentrated HNO_3 and $HClO_4$

For the four metals of interest, Pb was concentrated in Fraction V (35–60%) and Fraction III (20–44%), Zn in Fraction V (30–65%) and Fraction III (13–47%), and Cd in Fraction II (25–68%). Mn showed a more complex behavior, with the bulk of the Mn in the surface layers in the exchangeable fractions (I, II, and III) and a notable increase with depth of Mn in the nonexchangeable Fraction V. The authors ascribed this increase in the nonexchangeable fraction to either the precipitation of Mn^{4+} oxides or the incorporation of Mn in Fe oxyhydroxides. Metals concentrated in Fraction V would be essentially immobile in the surface environment.

Source: Lee et al. (1997).

Both elements are of environmental interest. Arsenic in very high concentrations (not those encountered in surface and ground waters, but perhaps due to human intervention) is a poison. Low-level, long-term exposure to arsenic may lead to an increased risk of cancer (National Academy of Sciences, 1999). For this reason, the USEPA (U.S. Environmental Protection Agency) has recommended lowering the allowable amount of arsenic in drinking water. The major anthropogenic source of arsenic is pesticides applied to orchards and other crop lands. Selenium is an essential metal for human health, but at slightly higher levels it becomes a toxic element. Certain plants can accumulate selenium, causing toxicity problems for ruminants that graze on the plants. The major anthropogenic source for selenium is deposition of atmospheric aerosols derived from the burning of coal.

Mercury Under a wide range of Eh–pH conditions mercury exists as mercury metal (remember that at room temperature mercury metal is a liquid). Liquid mercury is essentially insoluble in water, but mercury is transferred to the atmosphere by volatilization. Under strongly oxidizing conditions mercury exists either as the Hg^{2+} ion or its hydrolysis product $Hg(OH)_{2\,(aq)}$. In a reducing environment, if sulfur is present, mercury can form the insoluble sulfide HgS (cinnabar).

The global cycle of mercury is dominated by the vapor phase transport of Hg^0 (Figure 9–21). The residence time of mercury in the atmosphere is 1 year. However, because of the equilibrium between the atmosphere and the surface ocean, the rate constant for mercury removal from the atmosphere is 0.29 y^{-1}. Because of the low removal rate of mercury by the surface ocean, the bulk of the mercury is deposited on land, where it is sequestered in the soils.

In its metallic form mercury is essentially inert. While this means it does not represent an immediate environmental hazard, it also means that mercury can persist for an extended period of time in the natural environment. Certain microorganisms, such as anaerobic bacteria, can mediate the methylation of mercury (Figure 9–21) to monomethyl mercury (CH_3Hg) or dimethyl mercury [$(CH_3)_2Hg$], which are highly soluble species that are readily taken up by aquatic organisms, particularly fish and shellfish. The mercury is concentrated up the food chain and can reach concentrations of several thousand ppm in organisms residing at the highest trophic levels. At these concentration levels, mercury is

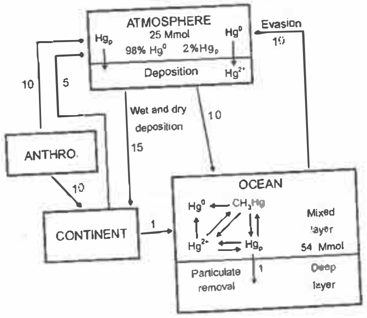

Figure 9–21
Present-day mercury cycle. The fluxes are given in Mmol L^{-1}. Hg_p represents mercury adsorbed to particles. Anthropogenic inputs are approximately 20 Mmol y^{-1}; half is returned to the surface close to the source and the other half is transferred to the atmosphere as volatile mercury. Adapted from Mason et al. (1994).

hazardous to human health. Because methylation of mercury is mediated by anaero bacteria, some of the mercury deposited in sediments in a reducing environment, eve sulfur is present, may be converted to soluble methyl species rather than insoluble merc sulfide.

Metal Variations in Space and Time A variety of approaches are used to determ both natural and anthropogenic distributions of metals in the surface environment. (such approach is a regional geochemical survey in which the metal content of so streams, and groundwater is determined (Reimann et al., 2001; Sewell, 1999). The purp of such studies is to gather information on both the background concentrations of the r als and areas of abnormally high metal concentrations. The bulk of these techniques v developed in the 1950s and 1960s, when they were used in geochemical exploration grams for base metal ore deposits. The sampling of different types of material can be u to infer the source of the metals. For example, Reimann et al. (2001) used four diffe sample materials: terrestrial moss, which predominantly reflects the atmospheric inpu metals; the O-soil horizon, which reflects the interplay among atmosphere, biosphere, lithosphere; the B-soil horizon, which reflects weathering processes; and the C-soil h zon, which represents the bedrock geochemistry.

The geochemical patterns can be compared to bedrock geology, surficial geolo land use, etc. Such studies have been greatly facilitated by the advent of Geograph Information Systems (GIS), which enables a multidimensional correlation of various rameters. For example, in the case of high levels of arsenic in groundwater, which have both natural (bedrock) and anthropogenic sources (pesticides), a compariso bedrock geology, land use, and arsenic well water concentrations can be used to dis guish between natural and anthropogenic sources of arsenic (Ayotte et al., 1999).

We are also interested in changes in metal concentrations with time. In Chapter 8 discussed how snow, ice, lake sediments, and biological indicators can be used to changes in atmospheric deposition of metals. In the case of the continental environm the most useful information is contained in lake sediments. In general, lake sediment the result of vertical sedimentation. As we have discussed in previous chapters, it is sible to determine the age of lake sediments as a function of depth. Chemical or iso analysis of the various layers can then be used to trace changes in anthropogenic input time.

Metal Contamination of Soils and Sediments A number of processes sequ metals in sediments. One way to look at the anthropogenic enrichment of metals in ments is to compare the abundance of the metals to background (or reference) values. of the commonly used references is average shale. The calculation is analogous to tha enrichment factors (discussed in Chapter 8); i.e.,

$$\text{Enrichment factor} = \frac{\text{Concentration in sediment}}{\text{Concentration in reference material}} \qquad (9$$

The geoaccumulation index (Müller, 1979) can be used to assess the degree of cont nation. The index is calculated as follows

$$I_{\text{geo}} = \log_2\left(\frac{C_n}{1.5B_n}\right) \qquad (9$$

where I_{geo} is the geoaccumulation index, $\log_2$ is log base 2, C_n is the concentration in sediment, and B_n is the background or reference concentration. After the geoaccum tion index has been calculated, it can be used to classify the sediment in terms of qu (Table 9–14).

Radioactive Isotopes and Radioactive Waste Disposal

Radioactive isotopes in the environment come from both natural sources (K, Th, and rocks and minerals) and anthropogenic sources (bomb testing, nuclear medicine, nuc accidents, and the nuclear fuel cycle). Radioactivity and radioactive decay were disc health hazard. At these higher concentrations fluoride can cause dental fluorosis (tooth mottling) and skeletal fluorosis (bone deformation and painful brittle joints). Natural sources of fluorine are volcanic emissions and the weathering of fluoride-containing minerals. Anthropogenic sources are mining and industrial emissions.

The concentration of fluoride in natural waters is largely controlled by dissociation reactions involving fluoride-containing minerals, of which the most important is fluorite. The dissociation reaction is

$$\mathrm{CaF}_{2\ \mathrm{fluorite}} \rightarrow \mathrm{Ca}^{2+} + 2\mathrm{F}^-$$

From the data in Appendix II, source 3, the equilibrium constant for this reaction, at 25°C, is

$$K_{\mathrm{fluorite}} = [\mathrm{Ca}^{2+}][\mathrm{F}^-]^2 = 10^{-10.51}$$

Writing this equation in logarithmic form gives

$$\log K_{\mathrm{fluorite}} = \log[\mathrm{Ca}^{2+}] + 2[\log \mathrm{F}^-] = -10.51$$

On a logarithmic plot, the relationship between the concentrations of the two ionic species in solution and fluorite solubility plots as a straight line (Figure 9–24). This is a very useful plot because it allows us to determine if a water is saturated with respect to fluorite, the major mineral controlling F^- concentrations. Consider a water sample of composition A. The water sample is undersaturated with respect to fluorite, and fluoride can be added to the water until it becomes saturated (A → B). At this point the concentration of fluoride will remain constant unless we reduce the Ca^{2+} concentration, in which case the F^- concentration can increase (B → C). If we increase the Ca^{2+} concentration (A → D), the solution will eventually become saturated in fluorite. Continued addition of Ca^{2+} will lead to a decrease in the F^- concentration in solution (D → E). It has been suggested that Ca^{2+} could be added (in the form of gypsum) to high F^- waters, leading to the precipitation of fluorite and a reduction in the F^- concentration. Most natural waters are undersaturated or just saturated with respect to fluorite, suggesting that fluorite solubility controls the F^- concentration of natural waters (Case Study 9–10).

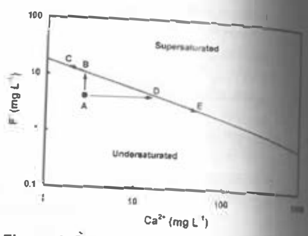

Figure 9–24
Solubility of fluorite at 25°C as a function of F^- and Ca^{2+} concentrations. See text for discussion.

Cl^- and Br^- Chlorine and bromine have both natural and anthropogenic sources. Natural sources include seawater, subsurface brines, and evaporite deposits. Anthropogenic sources for bromine include pesticides, medicines, industrial solvents, gasoline additives, and water purification. For chlorine, the list is even more extensive because it is one of the most widely used elements in modern industrial chemistry. Degradation of these anthropogenic compounds releases Cl^- and Br^- to solution, apparently largely in the form of simple ions. Hydrochemical characteristics of both compounds are (1) low concentration in most rock-forming minerals, (2) high solubility of most nonsilicate compounds, (3) virtually no adsorption by particles, (4) lack of volatile compounds, and (5) generally low bioconcentrations in aqueous systems. Because of these characteristics, both elements behave as conservative species and they have been widely used as tracers in hydrological systems. Bromine and chlorine, however, do differ in several important ways: (1) Bromide compounds are even more soluble than chloride compounds. During the formation of evaporite deposits Br is concentrated with respect to Cl in the late-stage brines, leading to a decrease in the Cl/Br ratio. (2) Br does show some adsorption characteristics, particularly at low pH, on kaolinite and iron oxide surfaces.

CASE STUDY 9–10

F^- Concentrations in Streams and Groundwaters from Nalgonda District, India

Ground and surface waters in the Nalgonda District of India contain elevated levels (0.4 to 20 mg L^{-1} for groundwater and 0.4 to 6.6 mg L^{-1} for surface waters) of fluoride, which has led to endemic fluorosis (Ramamohana Rao et al., 1993). There are no fluorine-based industries in the area (nor volcanoes), so the fluorine must originate from the minerals in the rocks and soils. The area is underlain by several varieties of granites that contain in the fluorine-bearing minerals fluorite (0 to 3.3%), biotite (0.1 to 1.7%), and hornblende (0.1 to 1.1%). Whole-rock F content ranges from 325 ppm to 3200 ppm, with a mean of 1440 ppm. Acid-soluble fluoride content (fluoride contained in fluorite and fluoroapatite, which can be removed by acid leaching) ranges from 40 to 1150 ppm, with a mean of 410 ppm. The overlying soils are also relatively high in fluoride, have relatively low Ca and Mg concentrations and high Na concentrations. There is an inverse relationship between hardness (Ca + Mg) and fluoride concentration and a direct relationship between alkalinity (due to the presence of Na in the soils) and fluoride concentration. All the soils have basic pH values. In a series of experiments the authors found that the solubility of fluorite was significantly increased in the presence of sodium carbonate and sodium bicarbonate, due to the following reactions:

$$\mathrm{CaF}_{2\ \mathrm{fluorite}} + 2\mathrm{Na}^+ + \mathrm{CO}_3^{2-} \rightarrow \mathrm{CaCO}_{3\ \mathrm{calcite}} + 2\mathrm{Na}^+ + 2\mathrm{F}^-$$

and

$$\mathrm{CaF}_{2\ \mathrm{fluorite}} + 2\mathrm{Na}^+ + 2\mathrm{HCO}_3^- \rightarrow \mathrm{CaCO}_{3\ \mathrm{calcite}} + 2\mathrm{Na}^+ + 2\mathrm{F}^- + \mathrm{H}_2\mathrm{O} + \mathrm{CO}_2$$

The authors concluded that these reactions led to the precipitation of calcite and a reduction in the amount of Ca^{2+} available for fluorite precipitation, thus increasing the amount of F^- in solution.

Source: Ramamohana Rao et al. (1993).

(3) There is some evidence that marine plants and surface plants do concentrate Br (Davis et al., 1998).

Because there are natural processes that will change the Cl/Br ratio, plus anthropogenic inputs that may lead to relative increases in Br or Cl concentrations and changes in the Cl/Br ratio, Davis et al. (1998) suggested that Cl/Br ratios could be used to fingerprint the sources of various waters in an aquifer. Once Cl and Br have entered a groundwater system, they tend to behave conservatively. Thus, variations in the Br/Cl ratio reflect variable degrees of end-member mixing. In Chapter 6 we developed mixing equations for isotopic systems. Analogous mixing equations can be written for conservative species. For a simple binary mixture involving two end members, the mathematics are straightforward if we use the abundances of the conservative species rather than ratios. For a mixture involving one conservative species and two end members, we can write

$$X_{\mathrm{M}} = X_{\mathrm{A}}f_{\mathrm{A}} + X_{\mathrm{B}}(1 - f_{\mathrm{A}}) \qquad (9\text{–}42)$$

where X_{M} is the concentration of species X in the mixture, X_{A} is the concentration of species X in end member A, X_{B} is the concentration of species X in end member B, and f_{A} (the mixing parameter) is the fraction of end member A. For a second conservative species in a mixture, we can write

$$Y_{\mathrm{M}} = Y_{\mathrm{A}}f_{\mathrm{A}} + Y_{\mathrm{B}}(1 - f_{\mathrm{A}}) \qquad (9\text{–}43)$$

where Y is the second conservative species. For a binary mixture involving conservative species, f_{A} must be the same for all species. We can solve equations 9–42 and 9–43 for f_{A} and equate the results:

$$f_{\mathrm{A}} = \frac{X_{\mathrm{M}} - X_{\mathrm{B}}}{X_{\mathrm{A}} - X_{\mathrm{B}}} = \frac{Y_{\mathrm{M}} - Y_{\mathrm{B}}}{Y_{\mathrm{A}} - Y_{\mathrm{B}}} \qquad (9\text{–}44)$$

Cross multiplying equation 9–44 and solving for Y_{M} gives

$$Y_{\mathrm{M}} = X_{\mathrm{M}}\frac{Y_{\mathrm{A}} - Y_{\mathrm{B}}}{X_{\mathrm{A}} - X_{\mathrm{B}}} + \frac{X_{\mathrm{A}}Y_{\mathrm{B}} - X_{\mathrm{B}}Y_{\mathrm{A}}}{X_{\mathrm{A}} - X_{\mathrm{B}}} \qquad (9\text{–}45)$$

which is the equation for a straight line (Figure 9–25, p. 368). For any simple binary mixture of two conservative species, the data will fall on a straight line. The purpose of this

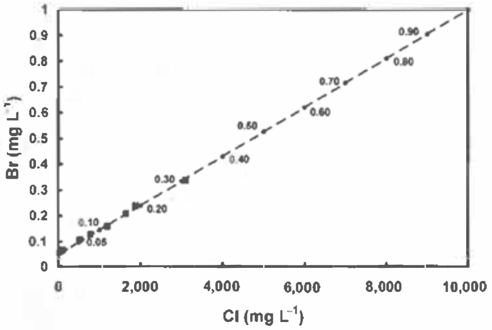

Figure 9–25

Binary mixture of groundwater (0.05 mg L^{-1} Br and 5 mg L^{-1} Cl) and brine (1 mg L^{-1} Br and 10,000 mg L^{-1} Cl). Labeled points are fraction of brine in the mixture. Groundwater samples from an aquifer (filled squares) fall along this line, suggesting they represent mixtures of uncontaminated groundwater and brine. The maximum amount of brine in the groundwater is approximately 31%.

exercise is to determine if a set of data obeys a simple binary mixing model. If the data do obey a simple binary mixing model, and if we know the composition of the end members, either equation 9–42 or 9–43 can be solved for the fraction of each end member in the individual samples. For example, groundwater samples were collected from a number of wells in an aquifer (filled squares in Figure 9–25). It is believed that subsurface brines are mixing with the groundwater. The well data plot on a straight line. The end-member compositions, based on measurements of groundwater entering the aquifer and the brine, are 0.05 mg L^{-1} of Br and 5 mg L^{-1} of Cl for the uncontaminated groundwater and 1 mg L^{-1} of Br and 10,000 mg L^{-1} of Cl for the brine. The labeled points on the diagram represent the fraction of brine. Inspection of Figure 9–25 reveals that the groundwater samples represent mixtures containing from 1% to about 31% brine.

Suppose our water samples consist of a mixture of three end members. As was discussed in Chapter 6, the data will fall within a triangular field. We can determine the fraction of the three end members in any particular sample using a graphical solution (Figure 6–14). If we know the end-member compositions, we can determine the fraction of each end member by solving a set of linear equations. For a three-end-member (A, B, and C) mixture, the concentration of X in the mixture is

$$X_M = X_A f_A + X_B f_B + X_C f_C \quad (9\text{–}46)$$

and the concentration of Y in the mixture is

$$Y_M = Y_A f_A + Y_B f_B + Y_C f_C \quad (9\text{–}47)$$

The symbols are as defined earlier. For our third equation,

$$f_A + f_B + f_C = 1 \quad (9\text{–}48)$$

because the total end-member fractions must add up to 1. Simultaneous solution of these three equations yields the end-member fractions.

Nitrogen

Nitrogen shows a complex and varied behavior in the natural environment (Figure 9–26). In Chapter 4 we constructed the Eh–pH diagram (Figure 4–9) for the various nitrogen species found in water. Depending on redox conditions, nitrogen can occur in natural wa-

DOCUMENT

4

METHOD 1314[1]

LIQUID-SOLID PARTITIONING AS A FUNCTION OF LIQUID-SOLID RATIO FOR CONSTITUENTS IN SOLID MATERIALS USING AN UP-FLOW PERCOLATION COLUMN PROCEDURE

SW-846 is not intended to be an analytical training manual. Therefore, method procedures are written based on the assumption that they will be performed by analysts who are formally trained in at least the basic principles of chemical analysis and in the use of the subject technology.

In addition, SW-846 methods, with the exception of required methods used for the analysis of method-defined parameters, are intended to be guidance methods that contain general information on how to perform an analytical procedure or technique, which a laboratory can use as a basic starting point for generating its own detailed standard operating procedure (SOP), either for its own general use or for a specific project application. Performance data included in this method are for guidance purposes only and must not be used as absolute quality control (QC) acceptance criteria for purposes of laboratory QC or accreditation.

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[1] This method has been derived from the CT001 procedure (Ref. 4) and is analogous to column percolation method CEN/TS 14405 (Ref. 5) developed for the Comité Européen de Normalisation (CEN).

1.0 SCOPE AND APPLICATION

1.1 This method is designed to provide the liquid-solid partitioning (LSP) of inorganic constituents (e.g., metals, radionuclides) and non-volatile organic constituents (e.g., polycyclic aromatic hydrocarbons (PAHs), dissolved organic carbon, etc.) in a granular solid material as a function of liquid-to-solid ratio (L/S) under percolation conditions. The first eluates of the column test may provide insight into the composition of pore solution either in a granular bed (e.g., soil column) or in the pore space of low-permeability material (e.g., solidified monolithic or compacted granular fill). Analyses of eluates for dissolved organic carbon and of the solid phase for total organic carbon afford evaluation of the impact of organic carbon release and the influence of dissolved organic carbon on the LSP of inorganic constituents.

1.2 This method is intended to be used as part of an environmental leaching assessment for the evaluation of disposal, beneficial use, treatment effectiveness, and site remediation. The method is not required by federal regulations to determine whether waste passes or fails the toxicity characteristic as defined at 40 CFR 261.24.

1.3 This method is suitable to a wide range of granular solid materials. Example materials include industrial wastes, soils, sludges, combustion residues, sediments, construction materials, and mining wastes. This method is not suitable to monolithic materials (e.g., cement-based and stabilized materials) without particle size reduction prior to testing.

1.4 This test method is intended as a means for obtaining a series of extracts (i.e., the eluates) of a granular solid material that may be used to show eluate concentrations and/or cumulative release as a function of L/S, which can be related to a time scale when data on mean infiltration rate, density and height of application are available.

1.5 This method provides options for the preparation of analytical samples that provide flexibility based on the level of detail required. For example, when the purpose of characterization is for comparison to previous testing, compositing of eluates may be possible to create a reduced set of analytical samples. Table 1 outlines the eluate fractions and collection options, based on whether concentration or cumulative release is to be reported. The collection schemes are described below.

1.5.1 Complete characterization

For complete characterization of eluate concentration and cumulative release as a function of L/S, nine discrete eluate collections and analyses are required (see Table 1, Option A). No compositing of eluate fractions is performed for complete characterization, and all eluate fractions are analyzed.

Eluate concentrations from complete characterization may be used in conjunction with information regarding environmental management scenarios to estimate anticipated leaching concentrations, release rates, and extents of release for individual material constituents in the management scenarios evaluated. Eluate concentrations may also be used along with geochemical speciation modeling to infer the mineral phases that control the LSP in the pore structure of the solid material.

1.5.2 Limited analysis

Under a limited analysis approach, nine eluate collections and analysis of six analytical samples are required. If evaluation is based on eluate concentrations, six discrete eluate fractions are chemically analyzed (see Table 1, Option B). If evaluation is based on cumulative release, some eluate fractions are composited by volume-weighted averaging to create a set of six analytical samples (see Table 1, Option C). The concentrations of composite analytical samples cannot be interpreted along with eluate fractions on the basis of concentration.

1.5.3 Index testing

For the determination of consistency between the subject material and previously characterized materials, nine eluate collections and analysis of three analytical samples are required. If consistency is to be determined by eluate concentrations, three discrete eluate fractions are chemically analyzed (see Table 1, Option D). If consistency is to be determined by cumulative release, some eluate fractions are composited by volume-weighted averaging to create a set of three analytical samples (see Table 1, Option E). The concentrations of composited analytical samples cannot be interpreted along with eluate fractions on the basis of concentration.

1.6 This method is not applicable to characterize the release of volatile organic analytes.

1.7 This method provides eluate solutions considered indicative of leachate under field conditions only where the field leaching pH is controlled by the alkalinity or acidity of the solid material and the field leachate is not subject to dilution or other attenuation mechanisms. The cumulative mass of constituent released over a L/S range may be considered an estimate of the maximum mass of that constituent to be leached under field leaching over intermediate timeframes (e.g., up to 100 years) and the domain of laboratory test pH.

1.8 Prior to employing this method, analysts are advised to take reasonable measures to ensure that the granular sample is homogenized to the most practical extent. Particle size reduction may provide additional assurance of sample homogenization.

1.9 In preparation of solid materials for use in this method, particle size reduction or exclusion of samples with large grain size is used to enhance the approach towards liquid-solid equilibrium over the residence time of eluent in the column.

1.10 The structure and use of this method is similar to that of NEN 7343 (see Ref. 3) and CEN/TS 14405 (see Ref. 5).

1.11 Prior to employing this method, analysts are advised to consult the base method for each type of procedure that may be employed in the overall analysis (e.g., Methods 9040, 9045 and 9050, and the determinative methods for the target analytes) for additional information on QC procedures, development of QC acceptance criteria, calculations, and general guidance. Analysts also should consult the disclaimer statement at the front of the manual and the information in Chapter Two for: 1) guidance on the intended flexibility in the choice of methods, apparatus, materials, reagents, and supplies, and 2) the responsibilities of the analyst for demonstrating that the techniques employed are appropriate for the analytes of interest, in the matrix of interest, and at the levels of concern.

In addition, analysts and data users are advised that, except where explicitly specified in a regulation, the use of SW-846 methods is *not* mandatory in response to federal testing requirements. The information contained in this method is provided by the Environmental Protection Agency (EPA or the Agency) as guidance to be used by the analyst and the regulated community in making judgments necessary to generate results that meet the data quality objectives (DQOs) for the intended application. Guidance on defining DQOs can be obtained at http://www.epa.gov/QUALITY/qs-docs/g4-final.pdf.

1.12 This method is restricted to use by, or under supervision of, properly experienced and trained personnel. Each analyst must demonstrate the ability to generate acceptable results with this method.

2.0 SUMMARY OF METHOD

Eluent is introduced into a column of moderately packed granular material in an up-flow pumping mode, with eluate collection performed as a function of the cumulative L/S. Up-flow pumping is used to minimize air entrainment and flow channeling. The default eluent for most materials is reagent water. However, a solution of 1.0 mM calcium chloride in reagent water is used when testing materials with either a high clay content (i.e., to prevent deflocculation of clay layers) or high organic matter (i.e., to moderate mobilization of dissolved organic carbon). The flow rate is maintained between 0.5-1.0 L/S per day to increase the likelihood of local equilibrium between the solid and liquid phases, due to residence times longer than one day. Eluate volumes are chemically analyzed for a combination of inorganic and non-volatile organic analytes depending on the constituents of potential concern (COPC). For the purposes of chemical speciation modeling, the entire eluent volume up to 10 mL/g dry sample (g-dry) is collected in nine specific aliquots of varying volume. A limited subset of eluent volumes within the same L/S range may be collected and analyzed for regulatory and compliance purposes. A flowchart for performing this method is shown in Figure 1.

3.0 DEFINITIONS

3.1 Constituent of potential concern (COPC) – A chemical species of interest, which may or may not be regulated, but may be characteristic of release-controlling properties of the sample geochemistry.

3.2 Release – The dissolution or partitioning of a COPC from the solid phase to the aqueous phase during laboratory testing (or under field conditions). In this method, mass release is expressed in units of mg COPC/kg dry solid material.

3.3 Liquid-solid partitioning (LSP) – The distribution of COPCs between the solid and liquid phases at the conclusion of the extraction.

3.4 Liquid-to-solid ratio (L/S) – The fraction of the total liquid volume (including the moisture contained in the "as-used" solid sample) to the dry mass equivalent of the solid material. L/S is typically expressed in volume units of liquid per dry mass of solid material (mL/g-dry).

3.5 "As-tested" sample – The solid sample at the conditions (e.g., moisture content and particle size distribution) present at the time of the start of the test procedure. The "as-tested" conditions will differ from the "as-received" sample conditions if particle size reduction and drying were performed.

3.6 Dry-mass equivalent – The mass of an "as-tested" (i.e., "wet") sample that equates to the mass of dry solids plus associated moisture, based on the moisture content of the "as-tested" material. The dry-mass equivalent is typically expressed in mass units of the "as-tested" sample (g).

3.7 Eluent – The solution used to contact the solid material in a leaching test. The eluent is usually free of COPCs but may contain other species used to control the test conditions of the extraction.

3.8 Eluate – The solution collected as an extract from a leaching test that contains the eluent plus constituents leached from the solid phase.

3.9 Refer to Chapter One, Chapter Three, and the manufacturer's instructions for definitions that may be relevant to this procedure.

4.0 INTERFERENCES

4.1 Solvents, reagents, glassware, and other sample processing hardware may yield artifacts and/or interferences during sample analysis. All of these materials must be demonstrated to be free from interferences under the conditions of the analysis by analyzing method blanks. Specific selection of reagents and purification of solvents by distillation in all-glass systems may be necessary. Refer to each method to be used for specific guidance on QC procedures and to Chapters Three and Four for general guidance on glassware cleaning. Also refer to Methods 9040, 9045 and 9050 and the determinative methods to be used for information regarding potential interferences.

4.2 When the test method is applied to solid materials with a clay content greater than 10% or an organic matter content greater than 1%, a solution of 1.0 mM calcium chloride in reagent water is recommended to minimize deflocculation of clay minerals. However, the use of calcium chloride solution will interfere with the determination of actual calcium and chloride release.

4.3 When this method is applied to fine-grained granular materials, tamping during column preparation may result in flow problems due to a low-permeability sample bed. This problem can be resolved by incorporating 20 - 50% inert material (e.g., 20-30-mesh normal sand or 2-mm borosilicate glass beads) into the solid sample. Alternatively, mass release from low-permeability materials may be measured using Method 1315.

5.0 SAFETY

5.1 This method does not address all safety issues associated with its use. The laboratory is responsible for maintaining a safe work environment and a current awareness file of Occupational Safety and Health Administration (OSHA) regulations regarding the safe handling of the chemicals specified in this method. A reference file of safety data sheets (SDSs) should be available to all personnel involved in these analyses.

5.2 During preparation and processing of extracts and/or eluents/eluates, some waste materials may generate heat or evolve potentially harmful gases when contacted with acids and bases. Adequate prior knowledge of the material being tested should be used to establish appropriate personal protection and workspace ventilation.

6.0 EQUIPMENT AND SUPPLIES

The mention of trade names or commercial products in this manual is for illustrative purposes only, and does not constitute an EPA endorsement or exclusive recommendation for use. The products and instrument settings cited in SW-846 methods represent those products and settings used during the method development or subsequently evaluated by the Agency. Glassware, reagents, supplies, equipment, and settings other than those listed in this manual may be employed provided that method performance appropriate for the intended application has been demonstrated and documented.

This section does not list common laboratory glassware (e.g., beakers and flasks) that might be used.

6.1 Column apparatus

This method recommends the use of a specific column apparatus (see Figure 2). Equipment with equivalent specifications may be substituted. The apparatus should have valves and quick connectors (e.g., Luer lock fittings) such that the column with end caps can be removed for packing with test material and mass measurements.

6.1.1 A 30-cm, straight cylindrical column with an inner diameter (ID) of 5 cm and constructed of inert material, resistant to high and low pH conditions and interaction with constituents of interest.

6.1.1.1 For the evaluation of inorganic COPC mobility, equipment composed of borosilicate glass (e.g., Kimble-Kontes CHROMAFLEX #420830-3020 or equivalent), polytetra-fluoroethylene (PTFE), high density polyethylene (HDPE), polypropylene (PP), or polyvinyl chloride (PVC) is recommended.

6.1.1.2 For the evaluation of non-volatile organic and mixed organic/inorganic COPCs, equipment composed of glass or Type 316 stainless steel is recommended. PTFE is not recommended for non-volatile organics, due to sorption of species with high hydrophobicity (e.g., PAHs). Borosilicate glass is recommended over other types of glass, especially when inorganic analytes are of concern.

6.1.2 The column must be of sufficient volume to accommodate a minimum of 300 g dry material plus a 1-cm layer of silica sand (20-30 mesh) used at the bottom of the column to distribute eluent flow and at the top of the column to form a coarse filter for eluate particulates.

6.1.3 The column must have end cap materials that form a leak-proof seal and that can withstand pressures, such as encountered when pumping eluent through the column.

6.2 Eluent feed stock container – Resealable bottle or other container, constructed of inert material, capable of withstanding extreme pH conditions and interaction with any constituents of interest (see guidance in Sec. 6.1.2)

6.3 Eluent feed tubing – 2-mm or similarly small ID tubing composed of chemically inert material such as PVC or equivalent

NOTE: Larger ID tubing may be required as a feed to the pump and manifold if a single eluent stock container is used to feed multiple column set-ups.

6.4 Eluate collection bottles – Capable of assembly with column apparatus using simple water locks in order to prevent the intrusion of air (see Figure 2)

6.5 20-30 mesh normal washed quartz sand

6.6 Balance – Capable of 0.01 g resolution for masses less than 500 g

6.7 Filtration apparatus – Pressure or vacuum filtration apparatus composed of appropriate materials so as to maximize the collection of extracts and minimize loss of the COPCs (e.g., Nalgene #300-4000 or equivalent) (see Sec. 6.1)

6.8 Filtration membranes – Composed of hydrophilic polypropylene or equivalent material with an effective pore size of 0.45 µm (e.g., Gelman Sciences GH Polypro #66548 from Fisher Scientific or equivalent)

6.9 pH meter – Laboratory model with the capability for temperature compensation (e.g., Accumet 20, Fisher Scientific or equivalent) and a minimum resolution of 0.1 pH units

6.10 pH combination electrode – Composed of chemically resistant materials

6.11 Conductivity meter – Laboratory model (e.g., Accumet 20, Fisher Scientific or equivalent), with a minimum resolution of 5% of the measured value

6.12 Conductivity electrodes – Composed of chemically resistant materials

7.0 REAGENTS AND STANDARDS

7.1 Reagent-grade chemicals, at a minimum, should be used in all tests. Unless otherwise indicated, all reagents should conform to the specifications of the Committee on Analytical Reagents of the American Chemical Society (ACS), where such specifications are available. Other grades may be used, provided the reagent is of sufficiently high purity to permit use without lessening the accuracy of the determination. Inorganic reagents and extracts should be stored in plastic to prevent interaction of constituents from glass containers.

7.2 Reagent water – Reagent water must be interference free. All references to water in this method refer to reagent water unless otherwise specified.

7.3 Calcium chloride (1.0 mM), $CaCl_2$ – Prepared by dissolving 0.11 g of ACS grade (or better) solid calcium chloride in 1 L of reagent water

8.0 SAMPLE COLLECTION, PRESERVATION, AND STORAGE

8.1 See Chapter Three, "Inorganic Analytes," and Chapter Four, "Organic Analytes," for sample collection and preservation instructions.

8.2 All samples should be collected using an appropriate sampling plan.

8.3 All containers should be composed of materials that minimize interaction with solution COPCs. For further information, see Chapters Three and Four.

8.4 Preservatives should not be added to samples before extraction.

8.5 Samples can be refrigerated, unless refrigeration results in an irreversible physical change to the sample.

8.6 Analytical extracts should be preserved according to the guidance given in the individual determinative methods for the COPCs.

8.7 Extract holding times should be consistent with the aqueous sample holding times specified in the determinative methods for the COPCs.

9.0 QUALITY CONTROL

9.1 Refer to Chapter One for guidance on quality assurance (QA) and quality control (QC) protocols. When inconsistencies exist between QC guidelines, method-specific QC criteria take precedence over both technique-specific criteria and Chapter One criteria, and technique-specific QC criteria take precedence over Chapter One criteria. Any effort involving the collection of analytical data should include development of a structured and systematic planning document, such as a quality assurance project plan (QAPP) or a sampling and analysis plan (SAP), which translates project objectives and specifications into directions for those who will implement the project and assess the results.

Each laboratory should maintain a formal QA program. The laboratory should also maintain records to document the quality of the data generated. Development of in-house QC limits for each method is encouraged. Use of instrument-specific QC limits is encouraged, provided such limits will generate data appropriate for use in the intended application. All data sheets and QC data should be maintained for reference or inspection.

9.2 In order to demonstrate the purity of reagents, at least one eluent blank should be tested. If multiple batches of eluent are employed, one eluent blank from each batch should be analyzed.

9.3 The analysis of extracts should follow appropriate QC procedures, as specified in the determinative methods for the COPCs. Refer to Chapter One for specific QC procedures.

9.4 Unless the "as-received" samples are part of a time-dependent (e.g., aging) study, solid materials should be processed and tested within one month of their receipt.

9.5 Initial demonstration of proficiency (IDP)

Leachate methods are not amenable to typical IDPs when reference materials with known values are not available. However, prior to using this method an analyst should have documented proficiency in the skills required for successful implementation of the method. For example, skill should be demonstrated in the use of an analytical balance, the determination of pH using Methods 9040 and 9045, and the determination of conductance using Method 9050.

10.0 CALIBRATION AND STANDARDIZATION

10.1 The balance should be calibrated and certified, at a minimum, annually or in accordance with laboratory policy.

10.2 Prior to measurement of eluate pH, the pH meter should be calibrated using a minimum of two standards that bracket the range of pH measurements. Refer to Methods 9040 and 9045 for additional guidance.

10.3 Prior to measurement of eluate conductivity, the meter should be calibrated using at least one standard at a value greater than the range of conductivity measurements. Refer to Method 9050 for additional guidance.

11.0 PROCEDURE

A flowchart for the method procedure is presented in Figure 1. Microsoft Excel® data templates are available to aid in collecting and archiving of laboratory and analytical data.[2]

11.1 Preparatory procedures – Particle size reduction (if required)

11.1.1 In this method, particle size reduction is used to prepare large-grained samples for the column test so that the approach toward liquid-solid equilibrium is enhanced and fluid channeling along column walls is minimized. The maximum particle size of the solid should ≤ 1/20 of the column diameter. For the column recommended in this method, a maximum particle size of 2.5 mm is acceptable. Therefore, 85% of the test material should pass through a 2.38-mm (U.S. No. 8) sieve. If less than 15% of the solid material is larger than the maximum acceptable particle size, this fraction of the solid may be excluded from the material tested, rather than particle size-reduced. The mass and nature of the discarded fraction should be documented.

11.1.2 Particle size reduction of an "as received" sample may be achieved through crushing, milling, or grinding with equipment made from chemically inert materials. During the reduction process, care should be taken to minimize the loss of sample and potentially volatile constituents in the sample.

11.1.3 If the moisture content of the "as received" material is greater than 15% (wet basis), air drying or desiccation may be necessary. Oven drying is not recommended for the

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[2] These Excel® templates form the basis for uploading method data into the data management program, LeachXS Lite™. Both the data templates and LeachXS Lite™ are available at http://vanderbilt.edu/leaching.

preparation of test samples due to the potential for mineral alteration and volatility loss. In all cases, the moisture content of the "as received" material should be recorded.

NOTE: If the solid material is susceptible to interaction with the atmosphere (e.g., carbonation, oxidation), drying should be conducted in an inert environment.

11.1.4 When the material seems to be of a relatively uniform particle size, calculate the percentage less than the sieve size as follows:

$$\% \text{ Passing} = \frac{M_{\text{sieved}}}{M_{\text{total}}} \times 100\%$$

Where: M_{sieved} = mass of sample passing the sieve (g)
M_{total} = mass of total sample (g) (e.g., M_{sieved} + mass not passing sieve)

11.1.5 The fraction retained by the sieve should be recycled for further particle size reduction until at least 85% of the initial mass has been reduced below the designated maximum particle size. Calculate and record the final percentage passing the sieve and the designated maximum particle size. For the uncrushable fraction of the "as-received" material, record the fraction mass and nature (e.g., rock, metal or glass shards, etc).

11.1.6 Store the size-reduced material in an airtight container in order to prevent contamination via gas exchange with the atmosphere. Store the container in a cool, dark, and dry place prior to use.

11.2 Determination of solids and moisture content

11.2.1 In order to provide the dry mass equivalent of the "as-tested" material, the solids content of the subject material should be determined. Often, the moisture content of the solid sample is recorded. In this method, the moisture content is determined and recorded on the basis of the "wet" or "as-tested" sample.

WARNING: The drying oven should be contained in a hood or otherwise properly ventilated. Significant laboratory contamination or inhalation hazards may result when drying heavily contaminated samples. Consult the laboratory safety officer for proper handling procedures prior to drying samples that may contain volatile, hazardous, flammable, or explosive materials.

11.2.2 Place a 5 to10-g sample of solid material into a tared dish or crucible. Dry the sample to a constant mass at 105 ± 2 °C. Check for constant mass by returning the dish to the drying oven for 24 hours, cooling to room temperature in a desiccator and re-weighing. The two mass readings should agree within the larger of 0.2% or 0.02 gram.

NOTE: The oven-dried sample is not used for the extraction and should be properly disposed once the dry mass is determined.

11.2.3 Calculate and report the solids content as follows:

$$SC = \frac{M_{dry}}{M_{test}}$$

Where: SC = solids content of "as-tested" material (g-dry/g)
M_{dry} = mass of dry material specified in the method (g-dry)
M_{test} = mass of "as-tested" solid equivalent to the dry-material mass (g)

11.2.4 Calculate and report the moisture content (wet basis) as follows:

$$MC_{wet} = \frac{M_{test} - M_{dry}}{M_{test}}$$

Where: MC_{wet} = moisture content on a wet basis (g_{H_2O}/g)
M_{dry} = mass of dry material specified in the method (g-dry)
M_{test} = mass of "as-tested" solid equivalent to the dry-material mass (g)

11.3 Apparatus preparation

11.3.1 Prepare the column test apparatus as depicted in Figure 2. Eluent feed should be directed through the lower end cap and upwards into the column to minimize air retention in the packed bed and fluid channeling along the column walls.

NOTE: When solid samples may be affected by dissolved oxygen in the feed stock, an inert gas (e.g., nitrogen or argon) may be bubbled through the feed solution to displace oxygen or used to purge the headspace above the feed solution.

NOTE: When alkaline or other air-sensitive eluates are expected, the vapor space of empty collection bottles may be purged with an inert gas (e.g., nitrogen or argon) prior to eluate collection.

11.4 Column packing

11.4.1 The column is packed with test material surrounded by layers of quartz sand at the top and bottom of the column to provide flow pattern regulation and coarse filtration.

NOTE: The following procedure describes the packing of the column from starting at the outflow (top) of the column and ending with the inflow (bottom) of the column. This is done to allow for a wider layer of quartz sand on the inflow side in cases where less than a full column of test material is available. The column is inverted prior to assembly into the leaching apparatus and initial wetting.

11.4.2 Record the mass of the empty column with end caps and any tubing leads or valves that would be needed to completely separate the column, which may include both solid material and water, from the entire apparatus.

11.4.3 Secure one end cap to the outflow side of the column and invert the column and end cap so that the outflow side of the column is facing downward.

11.4.4 Place an approximately 1-cm thick layer of quartz sand (Sec. 6.5) on the outflow side of the column using a small scoop or spoon. Record the mass of the column and sand layer. Level the sand layer by tapping the sides of the column.

11.4.5 Pack the main body of the column with a minimum 300-g dry-mass equivalent of "as-tested" sample in approximately five layers with light tamping with a glass or plastic rod to level the material between layers. When enough test material is available to produce a full column, the top of the packed sample should be approximately 1 cm from the level of the column interface with the inflow end cap (the end facing upwards). Record the mass of the column, lower sand layer, and "as-tested" sample.

11.4.6 Place a layer of sand to fill the remaining gap between the sample packing and the interface between the column and inflow end cap. When enough test material is available to pack a full column, the sand layer at the inflow end of the column should be approximately 1 cm. This gap may be larger if less test material is used. Record the total mass of the completely packed column.

11.4.7 Secure the inflow end cap. Invert the column so that the inflow end of the column is downward prior to inserting the column into the leaching apparatus.

11.4.8 Calculate the "as-tested" mass of the sample packing by subtracting the mass of the column and lower sand layer (Sec. 11.4.4) from the mass of the column, sand layer and packing (Sec. 11.4.5).

11.4.9 Calculate the dry mass equivalent packed of "as-tested" sample into the column using the solids content as follows:

$$\mathrm{M_{dry}} = \mathrm{SC} \cdot \mathrm{M_{test}}$$

Where: M_{dry} = dry-mass equivalent of sample in column (g-dry)
SC = solids content (g-dry/g)
M_{test} = mass of "as-tested" solid equivalent to the dry-material mass (g)

11.5 Pump setup

11.5.1 Prior to the start of the test, set the flow rate of the pump to a value that will provide an eluate production rate of 0.75 ± 0.25 L/S per day. For example, given a dry-mass equivalent of 300 g-dry, an L/S of 0.75 mL/g-dry would translate to a volume of 225 mL/g-dry, in which case the pump should be set to a flow rate of 225 mL (0.75 L/S) per day.

11.5.2 Prime the tubing with eluent

11.5.2.1 Detach the inlet tubing from the bottom of the column and place the open end into a waste container.

11.5.2.2 Turn on the pump and allow the inlet tubing to fill with eluent. Remove any air bubbles trapped in the inlet tubing.

11.5.2.3 When the inlet tubing is full with eluent, stop the pump and reconnect the tubing to the bottom of the column.

11.6 Eluent collection schedule

11.6.1 Table 2 provides a schedule of fraction end-point L/S, interval L/S, and eluate fraction volumes for collection, assuming a dry-mass equivalent of 300 g-dry. The minimum volume of each collection bottle should be scaled so as to capture the entire eluate fraction.

11.6.2 Using the assumed pump rate and the dry mass equivalent of the sample, estimate the durations of column testing required to reach the target eluate collection L/S shown in Table 2 as follows:

$$T_i = \frac{M_{dry} - \sum L/S_i}{R_i}$$

Where: T_i = target time from start for collection of eluent fraction, i (day)
M_{dry} = dry-mass equivalent of sample in column (g-dry)
$\sum L/S$ = target cumulative L/S for interval i from Table 1 (mL/g-dry)
R_i = pump rate assumed for interval, i (mL/day)

Alternatively, use the Microsoft Excel® spreadsheet template available at http://www.vanderbilt.edu/leaching/downloads/test-methods/ to develop the schedule of target collection times.

NOTE: The schedule of predicted collection times is for reference purposes only. Typically, the eluate collection rate is slower that predicted initially, due in part to pump inefficiency, back pressure, and dead-volume lag times. The decision to switch collection bottles should be made based on the volume of eluate collected with time. The schedule may be revised with each eluate fraction collected, so that the prediction of future collections may be more accurate. Pump flow rate adjustment may be necessary.

11.6.3 After each eluate collection, calculate the time required to reach the next collection time using the equation in 11.6.2 and the pump rate calculated from the previous collection interval.

NOTE: If eluate volumes other than those calculated for the fraction volume (i.e., T01, T02, etc.) are collected (e.g., manual collection will have inherent errors in the collection volumes), the cumulative L/S may quickly become out of alignment with the tolerances shown in Table 2. If this happens or appears to be likely, adjustments to the collection volumes for the two large collection fractions (i.e., T06 and T08) can be made in order to bring the cumulative L/S for subsequent collection intervals back in line with tolerances. The objective is to maintain the cumulative L/S target values for fractions T07 and T09. The Excel® data template available with LeachXS Lite™ can be helpful in maintaining target L/S ratios if updated after each collection interval. However, throughout the test, the user should ensure that the minimum eluate volume required for the chosen chemical analyses is collected.

11.7 Column test procedure – Column/eluent equilibration

11.7.1 Turn on the pump and allow the column to fill with eluent, thus wetting the column packing.

11.7.2 When the column packing is completely wetted and the eluent level is even with the top of the column (or just beginning to be seen through the effluent tubing at the top of the column apparatus), stop the pump and allow the column to equilibrate for 21 ± 3 hours.

11.8 Column test

11.8.1 Following equilibration, begin the column test by starting the pump and recording the date and time.

NOTE: The eluate production rate should be monitored frequently during the column test and the pump rate adjusted, such that the eluate production rate is maintained at approximately 0.75 ± 0.25 L/S per day.

11.8.2 When the eluate fraction has reached the target volume according to the predicted collection schedule, release the Luer lock connecting the active collection bottle and attach the eluent tubing to a new collection bottle.

NOTE: Alkaline eluate solutions may be susceptible to neutralization due to carbon dioxide uptake. When materials with alkaline pH are tested, precautions (e.g., purging collection bottles with inert gas) should be taken to prevent contact of the eluate with air.

11.9 Eluate processing

11.9.1 Decant a minimum volume (approximately 5 mL) of the eluate fraction from the collection vessel in order to measure the solution characteristics.

11.9.2 Measure and record the pH, specific conductivity, and oxidation-reduction potential (ORP) of the eluate (see Methods 9040, 9045 and 9050).

NOTE: Measurement of pH, conductivity, and ORP should be taken within 15 minutes of eluate processing (Sec. 11.9.1) to avoid neutralization of the solution due to exposure to carbon dioxide, especially when alkaline materials are tested.

NOTE: The measurement of ORP is optional, but strongly recommended, especially when testing materials where oxidation is likely to change the LSP of COPCs.

11.9.3 Separate any suspended particulates from the remaining liquid in the collection bottle by pressure or vacuum filtration through a 0.45-µm filtration membrane (Sec. 6.8).

NOTE: If either low volatility organic species or mercury is a COPC, pressure filtration is recommended over vacuum filtration in order to minimize volatility losses.

11.9.4 Immediately preserve and store the volume(s) of eluate required for chemical analysis. Preserve all analytical samples in a manner that is consistent with the determinative chemical analyses to be performed.

11.10 Reiterate Secs. 11.8.2 - 11.9.4 until nine eluate fractions are collected up to an L/S of 10 ± 0.2 mL/g-dry.

NOTE: The complete method requires that all nine eluate fractions be collected from the column. However, for purposes of limiting chemical analysis or index testing where interpretation may be based on cumulative release from the column, eluate fractions may be composited by volume-weighted averaging to create a single analytical sample from multiple eluate fractions (see Sec 11.11).

11.11 Analytical sample preparation options

This method allows for options in the preparation of analytical samples based on the detail of characterization required (e.g., complete, limited or index) and the basis for data reporting (e.g., concentration or cumulative release). However, the complete set of nine eluate fractions must be collected in all cases.

11.11.1 Table 1 shows the analytical preparation scheme for Options A-E described in the following sections. Each composite sample may be created either by combining the total eluate volumes and preserving the total sample for analysis; or combining aliquots of two eluate fractions using volume-weighted averages. However, it is recommended that composite analytical samples be prepared using aliquots of eluate fractions whenever possible, rather than whole eluate fractions. This approach allows for potential analysis of discrete eluate fractions, if desired, at a later date.

11.11.1.1 Option A – This sample preparation option is used for complete characterization and includes analysis of all eluate fractions. Since the entire cumulative release curve is captured in nine discrete fractions, reported data may be based on either eluate concentrations or cumulative release.

11.11.1.2 Option B – This sample preparation option is used only for limited analyses based on eluate concentration. Six discrete eluate fractions are analyzed. Data obtained using this option cannot be used for cumulative release since there are sections of the cumulative release curve not analyzed.

11.11.1.3 Option C – This sample preparation option is used only for limited analysis based on cumulative release. Six analytical samples are created from three discrete eluate fractions and three composite samples. In the scheme shown in Table 1, the following fractions are composited:

- T04 and T05
- T06 and T07
- T08 and T09

11.11.1.4 Option D – This sample preparation option is used only for index testing based on eluate concentration. Three discrete eluate fractions are analyzed. Data obtained using this option cannot be used for cumulative release since there are sections of the cumulative release curve not analyzed.

11.11.1.5 Option E – This sample preparation option is used only for index testing based on cumulative release. Three analytical samples are created from one discrete eluate fraction and two composite samples. In the scheme shown in Table 1, the following fractions are composited:

- T02, T03, T04, and T05
- T06, T07, T08, and T09

11.11.2 Volume-weighted composites

11.11.2.1 The volume of aliquots of eluate fractions for composite analytical samples may be calculated using the Excel template provided or the following formula:

$$V_i = \frac{F_i}{\sum_i^n F_i} \times V_{sample}$$

Where: V_i = the volume of an aliquot from eluate fraction, i (mL)
F_i = the collected volume of eluate fraction, i (mL)
V_{sample} = the total volume of the analytical sample (mL)
n = total number of eluate fractions to be composited

As an illustration of volume-weighted averaging, eluate fraction aliquots are calculated as required to create an analytical sample by compositing eluate fractions T06 through T09 for index testing based on cumulative release. The calculation follows the example volumes shown in Table 2 and assumes that an analytical sample volume of 100 mL is required.

$$\sum_i^n F_i = F_{T06} + F_{T07} + F_{T08} + F_{T09} = 450\text{ mL} + 150\text{ mL} + 1350\text{ mL} + 150\text{ mL} = 2100\text{ mL}$$

$$V_{T06} = \frac{F_{T06}}{\sum_i^n F_i} \times V_{sample} = \frac{450\text{ mL}}{2100\text{ mL}} \times 100\text{ mL} = 21.5\text{ mL}$$

$$V_{T07} = \frac{F_{T07}}{\sum_i^n F_i} \times V_{sample} = \frac{150\text{ mL}}{2100\text{ mL}} \times 100\text{ mL} = 7.1\text{ mL}$$

$$V_{T08} = \frac{F_{T08}}{\sum_i^n F_i} \times V_{sample} = \frac{1350\text{ mL}}{2100\text{ mL}} \times 100\text{ mL} = 64.3\text{ mL}$$

$$V_{T09} = \frac{F_{T09}}{\sum_i^n F_i} \times V_{sample} = \frac{150\text{ mL}}{2100\text{ mL}} \times 100\text{ mL} = 7.1\text{ mL}$$

$$V_{sample} = V_{T06} + V_{T07} + V_{T08} + V_{T09} = 21.5\text{ mL} + 7.1\text{ mL} + 64.3\text{ mL} + 7.1\text{ mL} = 100.0\text{ mL}$$

NOTE: The above illustration uses example eluate fraction volumes based on interval L/S ratios and an assumed test material mass. When calculating the aliquots of collected eluate fractions for composite samples, the actual collected fraction volumes should be used.

12.0 DATA ANALYSIS AND CALCULATIONS (Excel® template[3])

12.1 Data reporting

12.1.1 Figure 3 shows an example of a data sheet that may be used to report the concentration results of this method. At a minimum, the basic test report should include the following:

a) Name of the laboratory
b) Laboratory technical contact information
c) Date and time at the start of the test
d) Name or code of the solid material
e) Particle size (85 wt% less than designated particle size)
f) Packed bed dimensions (column ID and bed depth (cm))
g) Mass of solid material in column packing
h) Moisture content of solid material packed in column (g_{H_2O}/g)
i) Eluate specific information (see Sec. 12.1.2 below)

12.1.2 The minimum set of data that should be reported for each eluate includes:

a) Eluate sample ID
b) Eluate collection date and time
c) Amount of eluate collected (mass or volume)
d) Measured eluate pH
e) Measured eluate conductivity (mS/cm)
f) Measured ORP (mV) (optional)
g) Concentration of all COPCs
h) Analytical QC qualifiers as appropriate

12.2 Data Interpretation (optional)

12.2.1 Concentration as a function of L/S

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[3] Excel® data templates are provided to aid in collection and archiving of laboratory and analytical data. These templates form the basis for uploading method data into the data management program, LeachXS Lite™. Both the data templates and LeachXS Lite™ are available at http://vanderbilt.edu/leaching.

12.2.1.1 A curve of the eluate concentration as a function of L/S can be generated for each COPC after chemical analysis of all extracts by plotting the constituent concentration in the liquid phase as a function of the cumulative collected L/S ratio. The curve indicates the nominal equilibrium concentration of the constituent of interest as a function of L/S from 0 to 10 mL/g-dry at natural pH. An example curve is provided in Figure 4.

12.2.1.2 The lower limit of quantitation (LLOQ) of the determinative method for each COPC may be shown as a horizontal line. COPC concentrations below this line indicate negligible or non-quantitative concentrations.

NOTE: The LLOQ is highly matrix dependent and should be determined as part of a QA/QC plan.

12.3 Cumulative release as a function of L/S

12.3.1 The cumulative mass release of a COPC per unit solid material may be calculated as follows:

$$\Sigma \mathrm{M}_{\mathrm{i}} = \sum_{\mathrm{i}=1}^{9}\left[\mathrm{C}_{\mathrm{i}} \times \left(\Sigma \mathrm{L}/\mathrm{S}_{\mathrm{i}} - \Sigma \mathrm{L}/\mathrm{S}_{\mathrm{i}-1}\right)\right]$$

Where: ΣM_i = the cumulative mass release through interval i (mg/kg-dry)

C_i = the concentration of the COPC in the eluent collected during interval i (mg/L)

$\Sigma L/S_i$ = the cumulative L/S of eluate collected through interval i (L/kg-dry)

$\Sigma L/S_{i-1}$ = the cumulative L/S of eluate collected through interval i-1 (L/kg-dry)

12.3.2 Prepare a curve of the cumulative mass release generated for each COPC by plotting the cumulative mass release calculated in Sec. 12.3.1 as a function of the cumulative collected L/S. This curve provides an interpretation of the cumulative mass expected to be leached from a column of material as a function of L/S percolating through the column.

12.3.3 A comparison of the slope of the mass release curve to a unity slope, which is indicative of solubility-controlled release, may be made by plotting the cumulative mass release calculated in Sec. 12.3.1 versus the logarithm of the cumulative collected L/S. An example is provided in Figure 5.

12.4 Interpolation/extrapolation to target L/S values

The collected L/S dependence data may be interpolated or extrapolated to the nearest target L/S value for purposes of comparing different data sets (e.g., test replicates of the same or different materials). The most transparent and straightforward method is linear interpolation/extrapolation of data after $\log_{10}$ transformation.

12.4.1 Log_{10} transformation

Collected concentration values are transformed by taking the $\log_{10}$ of the measured concentration at each test position, i:

$$C_i = \log_{10}(c_i)$$

Where: C_i = $\log_{10}$-transformed concentration at test position i ($\log_{10}$[mL/g-dry])
c_i = the concentration measured at test position i (mg/L)

12.4.2 Linear interpolation/extrapolation

Given a set of coordinate data { ($\Sigma L/S_i$,C_i) : i = 1,...n } sorted by increasing order according to ΣL/S value (e.g., $\Sigma L/S_1 < \Sigma L/S_2 < \cdots < \Sigma L/S_n$), an interpolated/extrapolated $\log_{10}$-transformed concentration at a known L/S target is calculated as:

$$C_T = a_T + b_T \cdot \sum L/S_T$$

Where: C_T = the concentration at target ΣL/S value, $\Sigma L/S_T$ ($\log_{10}$[mg/L])
a_T and b_T are coefficients of the linear interpolation/extrapolation equation
$\Sigma L/S_T$ = a target pH value

Depending on the values of observed L/S values relative to target L/S values, the calculations of the coefficients a_T and b_T in the equation may differ according to the following algorithm:

If $\Sigma L/S_T < \Sigma L/S_1$, then $b_T = (C_2 - C_1) / (\Sigma L/S_2 - \Sigma L/S_1)$ and $a_T = C_2 - b_T \cdot \Sigma L/S_2$ (extrapolation from the two points with closest L/S values);

If $\Sigma L/S_T \geq \Sigma L/S_n$, then $b_T = (C_n - C_{n-1}) / (\Sigma L/S_n - \Sigma L/S_{n-1})$ and $a_T = C_n - b_T \cdot \Sigma L/S_n$ (extrapolation from the two points with closest L/S values);

If $\Sigma L/S_{j-1} \leq \Sigma L/S_T < \Sigma L/S_j$, then $b_T = (C_j - C_{j-1}) / (\Sigma L/S_j - \Sigma L/S_{j-1})$and $a_T = y_j - b_T \cdot \Sigma L/S_j$ (interpolation from the two closest points surrounding $\Sigma L/S_T$).

NOTE: Interpolation or extrapolation of data should only be conducted within a distance of ±20% of the target L/S value. Since the allowable L/S tolerance about a target L/S value is variable (see Table 2), interpolation/extrapolation should not create data at a target L/S value where collected data is missing.

13.0 METHOD PERFORMANCE

13.1 Performance data and related information are provided in SW-846 methods only as examples and guidance. The data do not represent required performance criteria for users of the methods. Instead, performance criteria should be developed on a project-specific basis, and the laboratory should establish in-house QC performance criteria for the application of this method. Performance data must not be used as absolute QC acceptance criteria for purposes of laboratory QC or accreditation.

13.2 Interlaboratory validation of this method was conducted using a contaminated smelter site soil (material code CFS) and a brass foundry sand (material code JaFS). Repeatability and reproducibility were determined at an L/S of 10 mL/g-dry for eluate concentration (see Table 3) and for cumulative mass released (see Table 4). More details on the interlaboratory validation may be found in Ref. 1.

13.3 Ref. 2 and Ref. 4 may provide additional guidance and insight on the use, performance, and application of this method.

14.0 POLLUTION PREVENTION

14.1 Pollution prevention encompasses any technique that reduces or eliminates the quantity and/or toxicity of waste at the point of generation. Numerous opportunities for pollution prevention exist in laboratory operations. The EPA has established a preferred hierarchy of environmental management techniques that places pollution prevention as the management option of first choice. Whenever feasible, laboratory personnel should use pollution prevention techniques to address their waste generation. When wastes cannot be feasibly reduced at the source, the Agency recommends recycling as the next best option.

14.2 For information about pollution prevention that may be applicable to laboratories and research institutions consult *Less is Better: Laboratory Chemical Management for Waste Reduction*, a free publication available from the ACS, Committee on Chemical Safety, https://www.acs.org/content/dam/acsorg/about/governance/committees/chemicalsafety/publications/less-is-better.pdf.

15.0 WASTE MANAGEMENT

The EPA requires that laboratory waste management practices be conducted consistent with all applicable rules and regulations. Laboratories are urged to protect air, water, and land by minimizing and controlling all releases from hoods and bench operations, complying with the letter and spirit of any sewer discharge permits and regulations, and by complying with all solid and hazardous waste regulations, particularly the hazardous waste identification rules and land disposal restrictions. For further information on waste management, consult *The Waste Management Manual for Laboratory Personnel* available at: http://www.labsafetyinstitute.org/FreeDocs/WasteMgmt.pdf.

16.0 REFERENCES

1. A.C. Garrabrants, D.S. Kosson, R. DeLapp, P. Kariher, P.F.A.B. Seignette, H.A. van der Sloot, L. Stefanski, and M. Baldwin, "Interlaboratory Validation of the Leaching Environmental Assessment (LEAF) Method 1314 and Method 1315," EPA 600/R-12/624, *U.S. Environmental Protection Agency*, Washington, DC, 2012.

2. A.C. Garrabrants, D.S. Kosson, H.A. van der Sloot, F. Sanchez, and O. Hjelmar, "Background Information for the Leaching Environmental Assessment Framework (LEAF) Test Methods," EPA/600/R-10-170, *U.S. Environmental Protection Agency*, Washington, DC, 2010.

3. NEN 7343, "Leaching Characteristics of Solid Earth and Stony Materials - Leaching Tests - Determination of the leaching of Inorganic Constituents from Powdery and Granular Materials with the Percolation Test," *Dutch Standardization Institute*, Delft, The Netherlands, 1995.

4. D.S. Kosson, H.A. van der Sloot, F. Sanchez, and A.C. Garrabrants, "An Integrated Framework for Evaluating Leaching in Waste Management and Utilization of Secondary Materials," *Environmental Engineering Science,*, 19(3) 159-204, 2002.

5. CEN/TS 14405, "Characterization of Waste - Leaching Behaviour Tests - Up-flow Percolation Test (Under Specified Conditions)," *Comité Européen de Normalisation*, Brussels, Belgium, 2004, 2004.

17.0 TABLES, DIAGRAMS, FLOWCHARTS, AND VALIDATION DATA

The following pages contain the tables and figures referenced by this method.

TABLE 1

SCHEDULE OF FRACTION COLLECTIONS AND ANALYTICAL SAMPLES

Fraction Label	ΣLS (mL/g-dry)	Option A: Characterization – Conc.	Option A: Characterization – ΣRel	Option B: Limited Analysis – Conc.	Option C: Limited Analysis – ΣRel	Option D: Index Testing – Conc.	Option E: Index Testing – ΣRel
T01	0.2 ± 0.1	✓	✓	✓	✓	✓	✓
T02	0.5 ± 0.1	✓	✓	✓	✓	X	↓
T03	1.0 ± 0.1	✓	✓	✓	✓	X	↓
T04	1.5 ± 0.2	✓	✓	X	↓	X	↓
T05	2.0 ± 0.2	✓	✓	✓	T05c	✓	✓T05c
T06	4.5 ± 0.2	✓	✓	X	↓	X	↓
T07	5.0 ± 0.2	✓	✓	✓	✓T07c	X	↓
T08	9.5 ± 0.2	✓	✓	X	↓	X	↓
T09	10.0 ± 0.2	✓	✓	✓	✓T09c	✓	✓T09c

NOTE: ΣRel = Cumulative release

✓ = Collect eluate fraction (or pool of fractions) as analytical sample

↓ = Composite eluate fraction with next fraction to create analytical sample

X = No fraction to collect

TABLE 2

SCHEDULE OF ELUATE FRACTIONS FOR COLLECTION WITH EXAMPLE VOLUMES

Interval Label	End Point ΣL/S (mL/g-dry)	Fraction L/S (mL/g-dry)	Example Fraction Volume (mL)
T01	0.2 ± 0.1	0.2	60
T02	0.5 ± 0.1	0.3	90
T03	1.0 ± 0.1	0.5	150
T04	1.5 ± 0.2	0.5	150
T05	2.0 ± 0.2	0.5	150
T06	4.5 ± 0.3	2.5	750
T07	5.0 ± 0.2	0.5	150
T08	9.5 ± 0.3	4.5	1350
T09	10.0 ± 0.2	0.5	150
B01	Eluent	N/A	100

NOTE: Example fraction volumes based on assumed packing mass of 300 g-dry

TABLE 3

METHOD PRECISION FOR ELUATE CONCENTRATION AT L/S=10 mL/g-dry

Analyte	Symbol	Repeatability – CFS %RSD_r	Repeatability – JaFS %RSD_r	Reproducibility – CFS %RSD_R	Reproducibility – JaFS %RSD_R
Aluminum	Al	8.6	12.7	16.6	28.2
Barium	Ba	6.9	13.9	23.0	24.2
Boron	B	11.9	14.4	14.3	23.9
Cadmium	Cd	9.2	-	14.6	-
Calcium	Ca	6.9	5.6	12.7	52.5
Copper	Cu	8.1	13.3	15.2	31.8
Magnesium	Mg	-	7.7	-	53.3
Manganese	Mn	-	22.0	-	26.6
Molybdenum	Mo	25.2	27.5	28.4	54.4
Lead	Pb	7.3	12.4	14.8	23.5
Thallium	Tl	9.6	-	19.2	-
Zinc	Zn	8.6	23.0	16.0	58.5

Material	Repeatability – CFS %RSD_r	Repeatability – JaFS %RSD_r	Repeatability – Overall	Reproducibility – CFS %RSD_R	Reproducibility – JaFS %RSD_R	Reproducibility – Overall
Mean	10%	15%	13%	18%	38%	28%

Data taken from Ref. 1.

TABLE 4

METHOD PRECISION FOR CUMULATIVE RELEASE AT L/S=10 mL/g-dry

Analyte	Symbol	Repeatability – CFS %RSD$_r$	Repeatability – JaFS %RSD$_r$	Reproducibility – CFS %RSD$_R$	Reproducibility – JaFS %RSD$_R$
Aluminum	Al	4.6	7.2	14.3	13.1
Barium	Ba	3.4	6.2	23.0	10.9
Boron	B	2.9	4.4	11.1	6.3
Cadmium	Cd	2.2	-	8.5	-
Calcium	Ca	2.1	3.6	8.2	19.9
Copper	Cu	3.9	4.6	15.3	21.4
Magnesium	Mg	-	4.2	-	17.2
Manganese	Mn	-	7.0	-	14.9
Molybdenum	Mo	4.4	4.5	12.3	11.1
Lead	Pb	1.8	9.5	10.8	15.1
Thallium	Tl	2.9	-	10.2	-
Zinc	Zn	4.0	7.3	11.3	18.6

Material	Repeatability – CFS %RSD$_r$	Repeatability – JaFS %RSD$_r$	Repeatability – Overall	Reproducibility – CFS %RSD$_R$	Reproducibility – JaFS %RSD$_R$	Reproducibility – Overall
Mean	3%	6%	5%	13%	15%	14%

Data taken from Ref. 1.

FIGURE 1

METHOD FLOWCHART

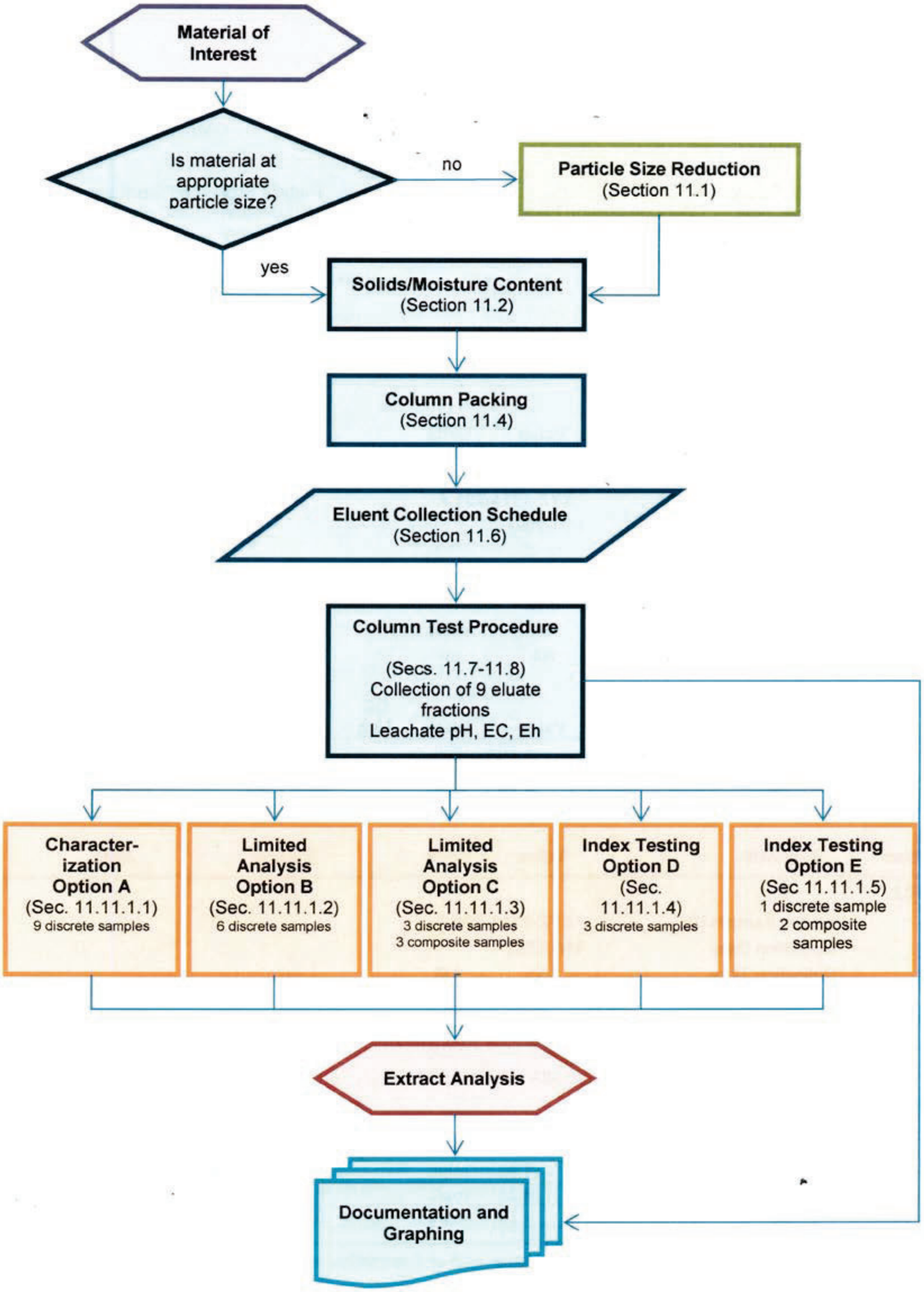
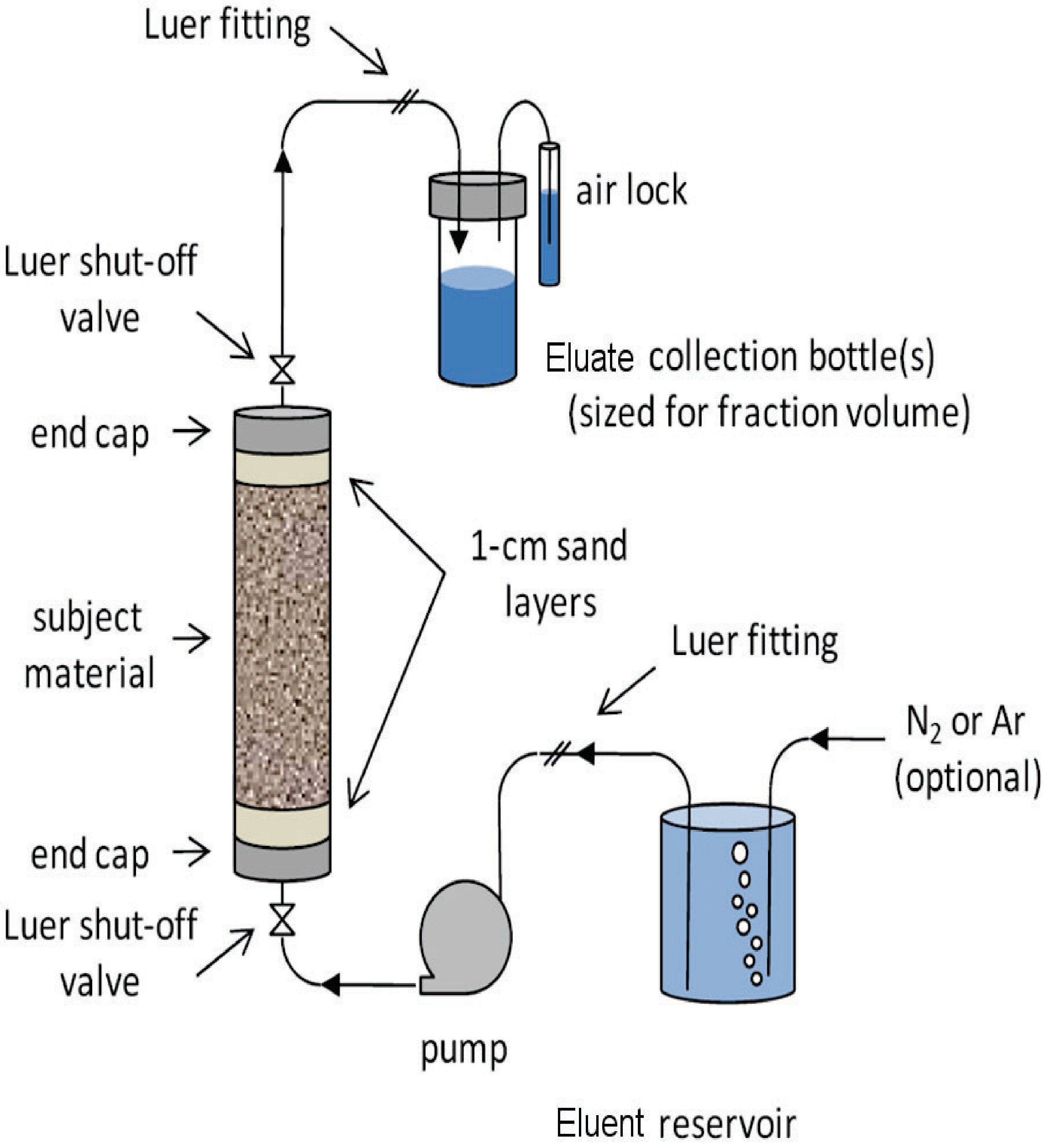


FIGURE 2

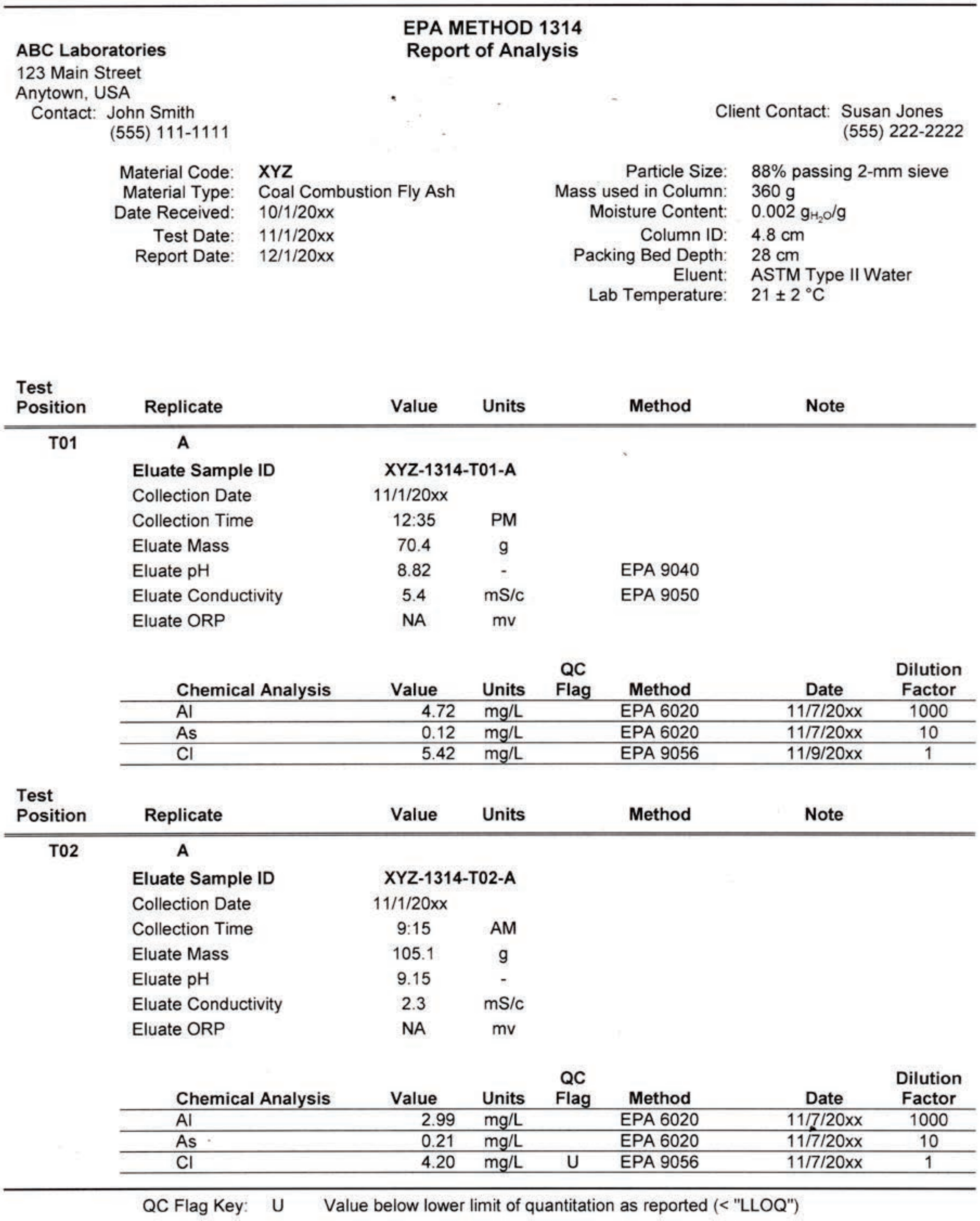
SCHEMATIC OF COLUMN TEST APPARATUS



NOTE: Figure not drawn to scale

FIGURE 3

EXAMPLE DATA REPORT FORMAT



EPA METHOD 1314
Report of Analysis

ABC Laboratories
123 Main Street
Anytown, USA
Contact: John Smith
(555) 111-1111

Client Contact: Susan Jones
(555) 222-2222

Material Code:	**XYZ**
Material Type:	Coal Combustion Fly Ash
Date Received:	10/1/20xx
Test Date:	11/1/20xx
Report Date:	12/1/20xx

Particle Size:	88% passing 2-mm sieve
Mass used in Column:	360 g
Moisture Content:	0.002 g_{H_2O}/g
Column ID:	4.8 cm
Packing Bed Depth:	28 cm
Eluent:	ASTM Type II Water
Lab Temperature:	21 ± 2 °C

Test Position	Replicate	Value	Units	Method	Note
T01	**A**				
	Eluate Sample ID	**XYZ-1314-T01-A**			
	Collection Date	11/1/20xx			
	Collection Time	12:35	PM		
	Eluate Mass	70.4	g		
	Eluate pH	8.82	-	EPA 9040	
	Eluate Conductivity	5.4	mS/c	EPA 9050	
	Eluate ORP	NA	mv		

Chemical Analysis	Value	Units	QC Flag	Method	Date	Dilution Factor
Al	4.72	mg/L		EPA 6020	11/7/20xx	1000
As	0.12	mg/L		EPA 6020	11/7/20xx	10
Cl	5.42	mg/L		EPA 9056	11/9/20xx	1

Test Position	Replicate	Value	Units	Method	Note
T02	**A**				
	Eluate Sample ID	**XYZ-1314-T02-A**			
	Collection Date	11/1/20xx			
	Collection Time	9:15	AM		
	Eluate Mass	105.1	g		
	Eluate pH	9.15	-		
	Eluate Conductivity	2.3	mS/c		
	Eluate ORP	NA	mv		

Chemical Analysis	Value	Units	QC Flag	Method	Date	Dilution Factor
Al	2.99	mg/L		EPA 6020	11/7/20xx	1000
As	0.21	mg/L		EPA 6020	11/7/20xx	10
Cl	4.20	mg/L	U	EPA 9056	11/7/20xx	1

QC Flag Key: U Value below lower limit of quantitation as reported (< "LLOQ")

FIGURE 4

EXAMPLE ELUATE CONCENTRATION CURVES FOR COMPLETE CHARACTERIZATION OF A COAL COMBUSTION FLY ASH

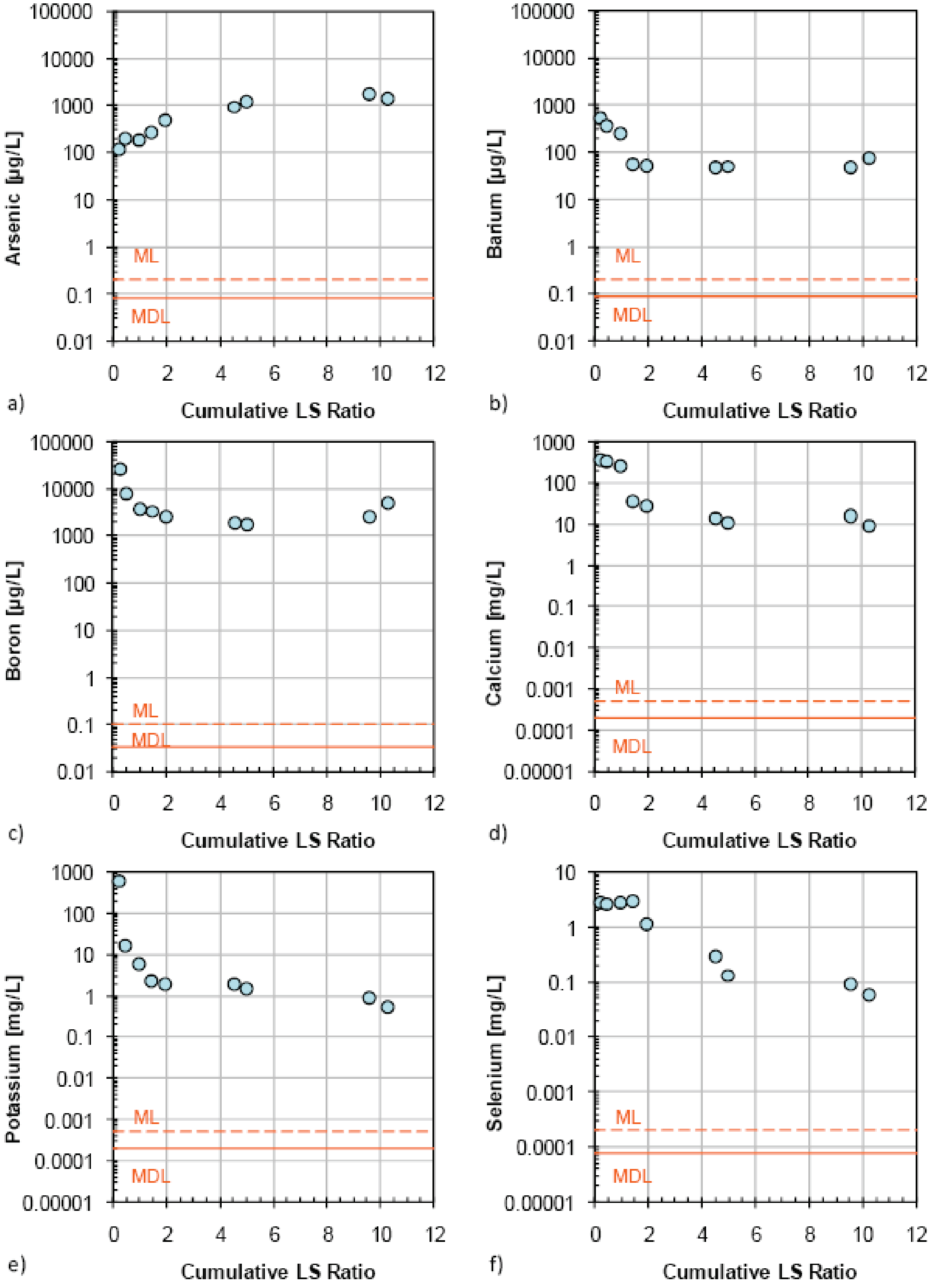
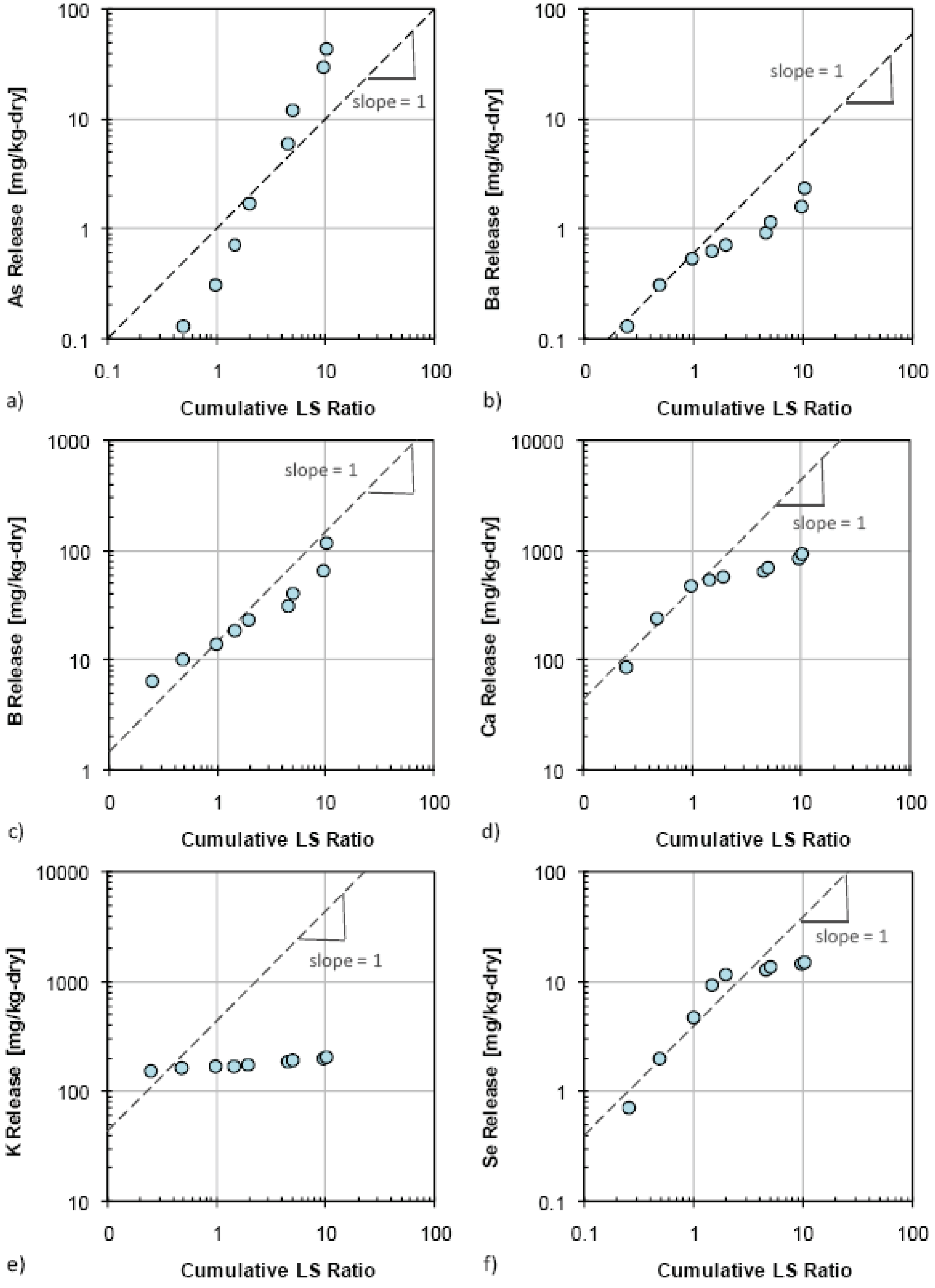


FIGURE 5

EXAMPLE CUMULATIVE RELEASE CURVES FOR COMPLETE CHARACTERIZATION OF A COAL COMBUSTION FLY ASH



<u>NOTE</u>: Dashed line represents solubility control (slope = 1).

DOCUMENT

5

METHOD 1315[1]

MASS TRANSFER RATES OF CONSTITUENTS IN MONOLITHIC OR COMPACTED GRANULAR MATERIALS USING A SEMI-DYNAMIC TANK LEACHING PROCEDURE

SW-846 is not intended to be an analytical training manual. Therefore, method procedures are written based on the assumption that they will be performed by analysts who are formally trained in at least the basic principles of chemical analysis and in the use of the subject technology.

In addition, SW-846 methods, with the exception of required methods used for the analysis of method-defined parameters, are intended to be guidance methods that contain general information on how to perform an analytical procedure or technique, which a laboratory can use as a basic starting point for generating its own detailed standard operating procedure (SOP), either for its own general use or for a specific project application. Performance data included in this method are for guidance purposes only and must not be used as absolute quality control (QC) acceptance criteria for purposes of laboratory QC or accreditation.

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[1] This method has been derived from the MT001 and MT002 procedures (Ref. 12). The method is analogous to the monolithic mass transfer methods NEN 7345 (Ref. 9) developed under Dutch regulation and CEN/TS 15863 (Ref. 13) developed for the Comité Européen de Normalisation (CEN).

1.0 SCOPE AND APPLICATION

1.1 This method is designed to provide the mass transfer rates (release rates) of inorganic analytes contained in a monolithic or compacted granular material, under diffusion-controlled release conditions, as a function of leaching time. Observed diffusivity and tortuosity may be estimated through analysis of the resulting leaching test data.

1.2 This method is suitable to a wide range of solid materials which may be in monolithic form (e.g., cements, solidified wastes) or may be compacted granular materials (e.g., soils, sediments and stacked granular wastes) which behave as a monolith, in that the predominant water flow is around the material and release is controlled by diffusion to the boundary. The method is not required by federal regulations to determine whether waste passes or fails the toxicity characteristic as defined at 40 CFR 261.24.

1.3 This leaching characterization method provides intrinsic material parameters for release of inorganic species under mass transfer controlled leaching conditions. This test method is intended as a means for obtaining a series of eluents which may be used to estimate the diffusivity of constituents and physical retention parameters of the solid material under specified laboratory conditions.

1.4 This method is not applicable to characterize the release of organic analytes with the exception of general dissolved organic carbon.

1.5 This method is a characterization method and does not provide a solution considered to be representative of eluate under field conditions. This method is similar in structure and use to predecessor methods such as MT001.1 (see Ref. 12), NEN 7345 (see Ref. 9), ANSI/ANS 16.1 (see Ref. 15), and ASTM C1308 (see Ref. 11). However, this method differs from previous methods in that: 1) leaching intervals are modified to improve QC; 2) sample preparation accounts for mass transfer from compacted granular samples; and, 3) mass transfer may be interpreted by more complex release models that account for physical retention of the porous medium and chemical retention at the pore wall through geochemical speciation modeling.

1.6 The geometry of monolithic samples may be rectangular (e.g., bricks or tiles), cubes, wafers or cylinders. Samples may also have a variety of faces exposed to eluent, forming anything from 1-dimensional (1-D) through 3-dimensional (3-D) mass transfer cases. In all cases, a minimum sample size of 5 cm in the direction of mass transfer must be employed and the liquid-surface-area ratio (L/A) must be maintained at 9 ± 1 mL/cm^2.

Monolithic samples should be suspended or held in the leaching fluid such that at least 98% of the entire sample surface area is exposed to eluent and the bulk of the eluent (e.g., a minimum of 2 cm between any exposed surface and the vessel wall) is in contact with the exposed sample surface. Figure 1 provides examples of appropriate sample holders and leaching configurations for 3-D and 1-D cases.

1.7 Compacted granular materials are granular solids, screened to pass through a 2-mm sieve, compacted following a modified Proctor compaction effort (see Ref. 10). The sample geometry must be open-faced cylinders due to limitations of mechanical packing. However, the diameter and height of the sample holder may be altered to correspond appropriately with the diameter and volume of the leaching vessel. In all cases, the sample size of at least 5 cm in the direction of mass transfer must be employed and the L/A must be maintained at 9 ± 1 mL/cm^2.

The sample should be positioned at the bottom of the leaching vessel with a minimum of 5 cm of distance between the solid-liquid interface and the top of the vessel. The distance between the non-leaching faces (i.e., outside of the mold surfaces) and the leaching vessel wall should be minimized to < 0.5 cm, such that the majority of the eluent volume is on top of the sample. Figure 2 shows an example of a holder and leaching configuration for a compacted granular sample.

1.8 The solvent system used in this characterization method is reagent water. Other systems (e.g., groundwater, seawater, and simulated liquids) may be used to infer material performance under specific environmental conditions. However, interaction between the eluent and the solid matrix may result in precipitation and pore blocking, which may interfere with characterization or complicate data interpretation.

1.9 Prior to employing this method, analysts are advised to consult the base method for each type of procedure that may be employed in the overall analysis (e.g., Methods 9040, 9045 and 9050, and the determinative methods for the target analytes) for additional information on QC procedures, development of QC acceptance criteria, calculations, and general guidance. Analysts also should consult the disclaimer statement at the front of the manual and the information in Chapter Two for: 1) guidance on the intended flexibility in the choice of methods, apparatus, materials, reagents, and supplies; and, 2) the responsibilities of the analyst for demonstrating that the techniques employed are appropriate for the analytes of interest, in the matrix of interest, and at the levels of concern.

In addition, analysts and data users are advised that, except where explicitly specified in a regulation, the use of SW-846 methods is *not* mandatory in response to federal testing requirements. The information contained in this method is provided by the Environmental Protection Agency (EPA or the Agency) as guidance to be used by the analyst and the regulated community in making judgments necessary to generate results that meet the data quality objectives for the intended application.

1.10 This method is restricted to use by, or under supervision of, properly experienced and trained personnel. Each analyst must demonstrate the ability to generate acceptable results with this method.

2.0 SUMMARY OF METHOD

This method comprises leaching of continuously water-saturated monolithic or compacted granular material in an eluent-filled tank with periodic renewal of the leaching solution. The vessel and sample dimensions are chosen such that the sample is fully immersed in the leaching solution. Monolithic samples may be cylinders or parallelepipeds, while granular materials are compacted into cylindrical molds at optimum moisture content using modified Proctor compaction methods (see Ref. 10). In either case, the exposure of a regular geometric area to the eluent is recommended. Samples are contacted with reagent water at a specified L/A. The leaching solution is exchanged with fresh reagent water at nine pre-determined intervals (see NOTE below). The sample is freely drained and the mass is recorded to monitor the amount of eluent absorbed into the solid matrix at the end of each leaching interval. The eluate pH and specific conductance is measured for each time interval and analytical samples are collected and preserved accordingly based on the determinative methods to be performed. Eluate concentrations are plotted as a function of time, as a mean interval flux, and as a cumulative release as a function of time. These data are used to estimate mass transfer parameters (i.e., observed diffusivity) for each constituent of potential concern (COPC). A flowchart for performing this method is shown in Figure 3.

NOTE: The leaching schedule may be extended for additional exchanges with individual intervals of 14 days to provide more information about longer-term release.

3.0 DEFINITIONS

3.1 Constituent of potential concern (COPC) – A chemical species of interest, which may or may not be regulated, but may be characteristic of release-controlling properties of the sample geochemistry.

3.2 Release – The dissolution or partitioning of a COPC from the solid phase to the aqueous phase during laboratory testing (or under field conditions). In this method, mass release is expressed in units of mg COPC/kg dry solid material.

3.3 Liquid-to-surface area ratio (L/A) – The ratio representing the total liquid volume used in the leaching interval to the external geometric surface area of the solid material. L/A is typically expressed in units of mL of eluent/cm^2 of exposed surface area.

3.4 Observed mass diffusivity – The apparent, macroscopic rate of release due to mass transfer from a solid into a liquid as measured using a leaching test under conditions where mass transfer controls release. The observed diffusivity accounts for all physical and chemical retention factors influencing mass transfer and is typically expressed in units of cm^2/s.

3.5 Effective mass diffusivity – The intrinsic rate of mass transfer in a porous medium accounting for physical retention. The effective mass diffusivity is typically expressed in units of cm^2/s.

3.6 Physical retention factor – A mass transfer rate term that describes the retardation of diffusion due to intrinsic physical properties of a porous medium (e.g., effective porosity, tortuosity).

3.7 Chemical retention factor – A mass transfer rate term that describes the chemical processes (e.g., dissolution/precipitation, adsorption/desorption, complexation) occurring at the pore water interface with the solid mineral phases within the porous structure of the solid material.

3.8 Eluent – The solution used to contact the solid material in a leaching test. The eluent is usually free of COPCs but may contain other species used to control the test conditions of the extraction.

3.9 Eluate – The solution collected as an extract from a leaching test that contains the eluent plus constituents leached from the solid phase.

3.10 Refer to Chapter One and Chapter Three, and the manufacturer's instructions for definitions that may be relevant to this procedure.

4.0 INTERFERENCES

4.1 Solvents, reagents, glassware, and other sample processing hardware may yield artifacts and/or interferences to sample analysis. All of these materials must be demonstrated to be free from interferences under the conditions of the analysis by analyzing method blanks. Specific selection of reagents and purification of solvents by distillation in all-glass systems may be necessary. Refer to each method to be used for specific guidance on QC procedures and to Chapters Three and Four for general guidance on glassware cleaning. Also refer to Methods 9040, 9045, and 9050 and the determinative methods to be used for information regarding potential interferences.

4.2 The reaction of atmospheric gases can influence the measured concentrations of constituents in eluates. For example, reaction of carbon dioxide with eluents from highly alkaline or strongly reducing materials will result in neutralization of eluate pH and precipitation of carbonates. Leaching vessels, especially those used when testing highly alkaline materials, should be designed to be airtight in order to minimize the reaction of samples with atmospheric gases.

4.3 Use of certain solvent systems may lead to precipitation at the material surface boundary, which may reduce mass transport rates. For example, exposure of cement-based materials to seawater leads to sealing of the porous block (see Ref. 8).

5.0 SAFETY

5.1 This method does not address all safety issues associated with its use. The laboratory is responsible for maintaining a safe work environment and a current awareness file of Occupational Safety and Health Administration (OSHA) regulations regarding the safe handling of the chemicals specified in this method. A reference file of safety data sheets (SDSs) should be available to all personnel involved in these analyses.

5.2 During preparation and processing of extracts and/or eluents/eluates, some waste materials may generate heat or evolve potentially harmful gases when contacted with acids and bases. Adequate prior knowledge of the material being tested should be used to establish appropriate personal protection and workspace ventilation.

6.0 EQUIPMENT AND SUPPLIES

The mention of trade names or commercial products in this manual is for illustrative purposes only, and does not constitute an EPA endorsement or exclusive recommendation for use. The products and instrument settings cited in SW-846 methods represent those products and settings used during the method development or subsequently evaluated by the Agency. Glassware, reagents, supplies, equipment, and settings other than those listed in this manual may be employed provided that method performance appropriate for the intended application has been demonstrated and documented.

This section does not list common laboratory glassware (e.g., beakers and flasks) that might be used.

6.1 Sample holder

6.1.1 Monolithic samples

6.1.1.1 A mesh or structured holder constructed of an inert material such as high density polyethylene (HDPE) or other material resistant to high and low pH is recommended.

6.1.1.2 The holder should be designed such that at least 98% of the external surface area of the sample may be exposed to eluent.

6.1.1.3 The holder should be designed to match the geometry of the mass transfer such that the bulk of the eluent may be in contact with the sample and the exposed surfaces of the sample centered within the leaching fluid.

NOTE: In the case of 1-D mass transfer from the axial face of a cylindrical sample, the outer diameter (OD) of the holder should be matched as closely as possible to the inner diameter (ID) of the leaching vessel so that the majority of the eluent is above the sample (e.g., in contact with the exposed material surface), while allowing for easy placement and removal of the holder in the leaching vessel (see Figure 1).

6.1.2 Compacted granular samples

6.1.2.1 A cylindrical mold constructed of an inert material such as HDPE or other material resistant to high and low pH is recommended.

6.1.2.2 The holder should be capable of withstanding the compaction force required to prepare the sample (see Sec. 11.3) without breaking or distorting.

NOTE: The outer diameter of the holder for a compacted granular sample should be matched as closely as possible to the inner diameter of the leaching vessel so that the majority of the eluent is above the sample (e.g., in contact with the exposed material surface) while allowing for easy placement and removal of the holder in the leaching vessel.

6.2 Leaching vessel

6.2.1 A straight-sided container constructed of a material resistant to high and low pH is recommended. Jars or buckets composed of HDPE, polycarbonate (PC), polypropylene (PP), or polyvinyl chloride (PVC) are recommended when evaluating the mobility of inorganic species.

6.2.2 The leaching vessel should have an airtight seal that can sustain long periods of standing without gas exchange with the atmosphere.

6.2.3 The container must be of sufficient volume to accommodate both the solid sample and an eluent volume based on an L/A of 9 ± 1 mL /cm^2 sample surface area. Ideally, the vessel should be sized such that the headspace is minimized within the tolerance of the L/A.

6.3 Leaching setup

Example photos of three possible leaching equipment arrangements for monolithic and compacted granular samples are shown in Figures 1 and 2, respectively. The equipment used in the each of these cases is described below.

6.3.1 Figure 1a shows a monolithic sample 3-D configuration with the following accessories:

- Sample holder – PP sink washers, 43-mm OD, 37-mm ID, 6-mm high, with four holes drilled at the quadrants to accept 2-mm OD nylon string knotted at the top
- Sample stand – PVC pipe, 47-mm OD, 51-mm high, cut to have four legs approximately 8-mm wide and 30-mm high
- Leaching Vessel – PP bucket, 140-mm ID at top, 120-mm ID at bottom, 200-mm high (Berry Plastics #T51386CP3, VWR Scientific, or equivalent)

6.3.2 Figure 1b shows a monolithic sample 1-D configuration with the following accessories:

- Sample holder – Polyethylene (PE) mold, 54-mm OD, 100-mm high (MA Industries, Peach Tree City, GA, or equivalent), with the test sample cured in mold and cut to 51-mm high
- Leaching vessel – 250-mL PC jar, 60-mm ID, 100-mm high (Nalgene #2116-0250, Fisher Scientific, or equivalent)

6.3.3 Figure 2 shows a compacted granular sample 1-D Configuration with the following accessories:

- Sample holder – PE mold, 100-mm OD, 200-mm high, (MA Industries, Peach Tree City, GA, or equivalent) cut to 63-mm high with three tabs drilled for 0.7-mm fishing line knotted at the top
- Leaching vessel – 1000-mL PC jar, 110-mm ID at top, 130-mm high (Nalgene #2116-1000, Fisher Scientific, or equivalent)
- Glass beads, borosilicate – 2-mm diameter

6.4 Filtration apparatus – Pressure or vacuum filtration apparatus composed of appropriate materials to maximize the collection of extracts and minimize the loss of COPCs (Nalgene #300-4000 or equivalent)

6.5 Filtration membranes – Composed of hydrophilic polypropylene or equivalent material with an effective pore size of 0.45 µm (e.g., Andwin Scientific GH Polypro 28143-288 or equivalent)

6.6 pH meter – Laboratory model with the capability for temperature compensation (e.g., Accumet 20, Fisher Scientific or equivalent) and a minimum resolution of 0.1 pH units

6.7 pH combination electrode – Composed of chemically resistant materials

6.8 Conductivity meter – Laboratory model (e.g., Accumet 20, Fisher Scientific or equivalent), with a minimum resolution of 5% of the measured value

6.9 Conductivity electrodes – Composed of chemically resistant materials

6.10 Proctor compactor (for compacted granular samples only) – Equipped with a slide hammer capable of dropping a 4.5-kg weight over a 0.46-m interval (see Ref. 10 for further details)

7.0 REAGENTS AND STANDARDS

7.1 Reagent-grade chemicals, at a minimum, should be used in all tests. Unless otherwise indicated, all reagents should conform to the specifications of the Committee on Analytical Reagents of the American Chemical Society (ACS), where such specifications are available. Other grades may be used, provided the reagent is of sufficiently high purity to permit its use without lessening the accuracy of the determination. Inorganic reagents and extracts should be stored in plastic to prevent interaction of constituents from glass containers.

7.2 Reagent water – Reagent water must be interference-free. All references to water in this method refer to reagent water unless otherwise specified.

7.3 Other reagents may be used in place of reagent water on a case-specific basis.

8.0 SAMPLE COLLECTION, PRESERVATION, AND STORAGE

8.1 See Chapter Three, "Inorganic Analytes," and Chapter 4, "Organic Analytes," for sample collection and preservation instructions.

8.2 Both plastic and glass containers are suitable for the collection of samples. All sample containers must be prewashed with a metal-free detergent and triple-rinsed with nitric acid and reagent water, depending on the history of the container. For further information, see Chapter Three.

9.0 QUALITY CONTROL

9.1 Refer to Chapter One for guidance on quality assurance (QA) and quality control (QC) protocols. When inconsistencies exist between QC guidelines, method-specific QC criteria take precedence over both technique-specific criteria and Chapter One criteria, and technique-specific QC criteria take precedence over Chapter One criteria. Any effort involving the collection of analytical data should include development of a structured and systematic planning document, such as a quality assurance project plan (QAPP) or a sampling and analysis plan (SAP), which translates project objectives and specifications into directions for those who will implement the project and assess the results.

Each laboratory should maintain a formal QA program. The laboratory should also maintain records to document the quality of the data generated. Development of in-house QC limits for each method is encouraged. Use of instrument-specific QC limits is encouraged, provided such limits will generate data appropriate for use in the intended application. All data sheets and QC data should be maintained for reference or inspection.

9.2 In order to demonstrate the purity of reagents and sample contact surfaces, method blanks should be tested for each leaching interval. Refer to Chapter One for specific QC procedures.

9.3 The analysis of extracts should follow appropriate QC procedures, as specified in the determinative methods for the COPCs. Refer to Chapter One for specific QC procedures.

9.4 Initial demonstration of proficiency (IDP)

Leachate methods are not amenable to typical IDPs when reference materials with known values are not available. However, prior to using this method an analyst should have documented proficiency in the skills required for successful implementation of the method. For example, skill should be demonstrated in the use of an analytical balance, the determination of pH using Methods 9040 and 9045 and the determination of conductance using Method 9050.

10.0 CALIBRATION AND STANDARDIZATION

10.1 The balance should be calibrated and certified, at a minimum, annually or in accordance with laboratory policy.

10.2 Prior to measurement of eluate pH, the pH meter should be calibrated using a minimum of two standards that bracket the range of pH measurements. Refer to Methods 9040 and 9045 for additional guidance.

10.3 Prior to measurement of eluate conductivity, the meter should be calibrated using at least one standard at a value greater than the range of conductivity measurements. Refer to Method 9050 for additional guidance.

11.0 PROCEDURE

A flowchart of this method is presented in Figure 3. Microsoft Excel® data templates are available to aid in collecting and archiving of laboratory and analytical data.[2]

11.1 Preparatory Procedures – Determination of solids and moisture content

The moisture and solids content of the sample material are used to relate leaching results to dry-material masses. When preparing compacted granular samples for testing, the moisture content or solid content is used to determine the optimum moisture content following the modified Proctor test. This method calculates moisture content on the basis of the "wet" or "as-tested" sample.

WARNING: The drying oven should be contained in a hood or otherwise properly ventilated. Significant laboratory contamination or inhalation hazards may result when drying heavily contaminated samples. Consult the laboratory safety officer for proper handling procedures prior to drying samples that may contain volatile, hazardous, flammable, or explosive materials.

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[2] These Excel® templates form the basis for uploading method data into the data management program, LeachXS Lite™. Both the data templates and LeachXS Lite™ are available at http://vanderbilt.edu/leaching.

11.1.1 Place 5 - 10 g of solid sample material into a tared dish or crucible. Dry the sample to a constant mass at 105 ± 2 °C. Check for constant mass by returning the dish to the drying oven for 24 hours, cooling to room temperature in a desiccator and re-weighing. The two mass readings should agree within the larger of 0.2% or 0.02 g.

NOTE: The oven-dried sample is not used for the extraction and should be properly disposed of once the dry mass is determined.

11.1.2 Calculate and report the solids content as follows:

$$SC = \frac{M_{dry}}{M_{test}}$$

Where: SC = solids content of "as-tested" material (g-dry/g)
M_{dry} = mass of dry material specified in the method (g-dry)
M_{test} = mass of "as-tested" solid equivalent to the dry-material mass (g)

11.1.3 Calculate and report the moisture content (wet basis) as follows:

$$MC_{wet} = \frac{M_{test} - M_{dry}}{M_{test}}$$

Where: MC_{wet} = moisture content on a wet basis (g_{H_2O}/g)
M_{dry} = mass of dry material specified in the method (g-dry)
M_{test} = mass of "as-tested" solid equivalent to the dry-material mass (g)

11.2 Preparation of monolithic samples

11.2.1 If the material to be tested is granular, disregard this section and proceed to Sec. 11.3.

11.2.2 A representative sample of monolithic material should be obtained by molding material components in place (e.g., cementitious media) or by coring or cutting a sample from a larger existing specimen.

11.2.3 The geometry of monolithic samples may be rectangular (e.g., bricks or tiles), cubes, wafers, or cylinders. Samples may also have a variety of faces exposed to eluent forming 1-, 2-, or 3-D mass transfer cases. Examples of monolithic sample leaching setups are shown in Figure 1.

11.2.4 A minimum sample size of 5 cm in the direction of mass transfer must be employed and the L/A must be maintained at 9 ± 1 mL/cm^2.

NOTE: Since the sample holder and leaching vessel must correspond to the specifications in Sec. 6.1, it is often easier to modify the sample size and geometry rather than the holder and vessel dimensions.

11.2.5 Proceed to Sec. 11.4.

11.3 Preparation of compacted granular samples

Compacted granular materials, in most cases, must be open-faced cylinders due to the limitations of mechanical packing. However, the diameter and height of the sample holder may be altered to work appropriately with the diameter and volume of the leaching vessel. In all cases, a minimum sample size of 5 cm in the direction of mass transfer must be employed and the L/A must be maintained at 9 ± 1 mL/cm^2.

Granular samples are compacted into the sample holder using a variation on the modified Proctor compaction (see Ref. 10) to include the use of 6-cm high-test molds. Shorter or taller molds (or packing depths) may be used as long as the compaction effort of 56,000 ft-lb$_f$/ft^3 is achievable. The number of packing layers should be maintained at the five layers specified in Ref. 10. However, the number of blows per layer in a 4-in diameter mold may be changed according to the follow formula:

$$\frac{56{,}000\,\text{ft - lb}_\text{f}}{\text{ft}^3}\,\Bigg|\,\frac{\text{blow}}{1.5\,\text{ft}\times 10\,\text{lb}_\text{f}}\,\Bigg|\,\frac{\pi\left(0.\overline{3}/2\ \text{ft}\right)^2\times h\,\text{ft}}{5\,\text{layer}} = \frac{65.2\times h\,\text{blow}}{\text{layer}}$$

Where: *h* is the measured height of the sample mold (ft).

Thus, for the mold height of 4.584 in (0.382 ft) specified in the ASTM procedure, 25 blows per each of 5 layers are required. When a 6-cm (0.196 ft) mold height is used (as suggested in this method), 13 blows per each of 5 layers are required to obtain the same compaction effort.

The granular sample should be compacted at a moisture content corresponding to 90% of the modified Proctor optimum packing density in order to provide a uniform approach to obtaining a sample density that approximates field conditions. Optimum moisture content refers to the amount of moisture or fractional mass of water (g_{H_2O}/g material) in the granular sample that is present at the optimum packing density (g-dry material/cm^3). Optimum packing density is defined in Ref. 10. The optimum moisture content of the test material is determined from a pre-test that measures the packing density of granular materials compacted at different levels of moisture content.

11.3.1 Pre-test to determine optimum moisture content

The pre-test is conducted as a series of five batch-wise packing trials with consecutive increases in moisture content until the maximum packing density has been surpassed. The optimum moisture content is determined as the maximum of a third-order polynomial fit through the graph of dry-packing density as a function of moisture content (wet basis).

11.3.1.1 Place 1500 g of "as received" material into a pail or bowl and mix well by hand to homogenize. As an alternative to hand mixing, a mechanical paddle mixer may be used.

NOTE: The pre-test may be conducted from a bulk supply of solid material (e.g., 10 kg total for five batches) as long as the starting mass for each trial is recorded and incremental water additions are used.

11.3.1.2 Mix a known amount of tap water with the bulk material in the pail or bowl until homogenized based on visual inspection. For the first point in the pre-test, no water needs to be added.

NOTE: The amount of water added should be enough to increase the moisture content in approximately 3 - 5% increments. Smaller additions may be needed in order to provide finer resolution of the packing density as a function of the moisture content curve.

11.3.1.3 Calculate the new moisture content (wet basis) for the trial as follows:

$$MC^{i}_{(wet)} = \frac{M_{test} \times MC_{wet} + W_{added}}{M_{test} + W_{added}}$$

Where: $MC^{i}_{(wet)}$ = moisture content on a wet basis of the pre-test trial (g_{H_2O}/g)

M_{test} = mass of "as-tested" solid equivalent to the dry-material mass (g)

$MC_{(wet)}$ = moisture content on a wet basis of the "as-tested" material (g_{H_2O}/g)

W_{added} = mass of water added to the "as-tested" material (g_{H_2O}/g)

11.3.1.4 Compact approximately 1000 g of material into a tared 10-cm diameter mold into three consecutive layers of material. The compacted mass should have a level, flat surface as a top face.

11.3.1.5 Measure and record the height, diameter, and mass of the resulting compacted material.

11.3.1.6 Calculate and record the packing density (dry basis) as follows:

$$\rho_{pack} = \frac{m \times SC}{\pi \times h}\left(\frac{2}{d}\right)^2$$

Where: ρ_{pack} = packing density (dry basis) (g-dry/cm^3)

m = mass of the compacted sample (g)

SC = solids content of "as-tested" granular material (g-dry/g)

d = measured diameter of the compacted sample (cm)

h = measured height of the compacted sample (cm)

11.3.1.7 Repeat Sec. 11.3.1.1 - 11.3.1.6 for four subsequent trials until the value of the calculated packing density decreases.

11.3.1.8 Plot the packing density as a function of moisture content. Figure 4 shows an example of a packing density curve.

11.3.1.9 Determine the optimum moisture content at the maximum of the packing density curve. This value may be read directly from the graph or determined by the maximum of a third-order polynomial fit through the five pre-test data points (see the Microsoft Excel® spreadsheet template available at http://www.vanderbilt.edu/leaching/downloads/test-methods/).

11.3.2 Compacted granular test sample preparation

11.3.2.1 Using the optimum moisture content determined in Sec. 11.3.1.9, calculate the amount of "as-received" material that is required to pack the sample holder to within 3 mm of the rim of the holder.

$$M_{test} = \frac{\rho_{opt} \times \pi \times \left(h - 0.3\right)}{SC}\left(\frac{d}{2}\right)^2$$

Where: M_{test} = mass of "as tested" solid equivalent to the dry-material mass (g)
ρ_{opt} = optimal packing density (dry basis) (g-dry/cm^3) – determined in Sec. 11.3.1.9
h = measured height of the sample mold (cm)
SC = solids content of "as-tested" granular material (g-dry/g)
d = measured diameter of the sample mold (cm)

11.3.2.2 Adjust the moisture content of the "as-received" material to the optimum moisture content using reagent water and mix until homogenized.

11.3.2.3 Pack the sample material into the sample holder using the modified Proctor compaction as described in Ref. 10.

11.3.2.4 Place a monolayer of borosilicate glass beads (Sec. 6.3.3) on the exposed sample surface to minimize scouring and mass loss during testing.

11.3.2.5 Begin the leach test procedure promptly or cover the sample with plastic wrap to minimize moisture loss to the atmosphere.

11.4 Leaching procedure

This protocol is a semi-dynamic, tank-leaching procedure (see schematic in Figure 5) where the sample is exposed to eluate for a series of leaching intervals interspersed with eluent exchanges. The chemical composition of each eluate is determined and mass transfer from the bulk solid is determined as a function of cumulative leaching time. The schedule of leaching intervals for this method is shown in Table 1.

11.4.1 Pre-test measurements – For the surface area calculation, measure and record the dimensions of the test specimen. This should include the diameter and height for a cylinder; length, width, and depth for a parallelepiped; or diameter of exposed surface for a compacted granular sample.

11.4.2 Measure and record the mass of the specimen. This value should be monitored for each eluent exchange.

11.4.3 If a holder is used, place the specimen in the monolith holder.

11.4.4 Measure and record the mass of the specimen and holder, if applicable.

11.4.5 The recommended temperature for conducting this method is room temperature (20 ± 2 °C). When conducted at temperature readings or variations other than those recommended, record the ambient temperature at each eluent renewal.

11.5 Eluent exchange

11.5.1 Fill a clean leaching vessel with the required volume of reagent water based on an L/A of 9 ± 1 mL/cm^2. Record the amount of eluent used.

11.5.2 Carefully place the specimen or the specimen and holder in the leaching vessel (Figure 6a) so that the sample is centered in the eluent (see Figure 6b). Submersion should be gentle enough so that the physical integrity of the monolith is maintained and scouring of the solid is minimized.

11.5.3 Cover the leaching vessel with the airtight lid and place in a safe location until the end of the leaching interval. Table 1 shows the schedule of leaching intervals and cumulative release times for this method.

NOTE: Eluates of alkaline materials may be susceptible to neutralization through reaction with carbon dioxide. Precautions (e.g., ensuring airtight vessels or purging headspace) should be taken to minimize the effect of carbonation on eluates that may sit stationary for more than one week.

11.5.4 Prior to the end of the leaching interval, repeat Sec. 11.5.1 in order to prepare a vessel for the next leaching interval.

11.5.5 At the end of the leaching interval (see Table 1), carefully remove the specimen or the specimen and holder from the vessel (Figure 6c). Drain the liquid from the surface of the specimen into the eluate for approximately 20 sec.

11.5.6 Measure and record the mass of the specimen or the mass of the specimen and holder (Figure 6d).

NOTE: The change in sample mass between intervals is an indication of the potential absorption of eluent by the matrix (mass gain) or erosion of the matrix (mass loss). In the case where a holder is used, moisture may condense on the holder during the leaching interval and sample absorption may not be evident.

NOTE: Mass gain may also be indicative of carbonate precipitation if the vessel is not tightly sealed and carbon dioxide is absorbed from the atmosphere.

11.5.7 Place the specimen or the specimen and holder into the clean leaching vessel filled with new eluent as prepared in Sec. 11.5.4.

11.5.8 Cover the new leaching vessel with the airtight lid and place in a safe location until the end of the leaching interval.

11.6 Eluate processing

11.6.1 Measure and record the pH, specific conductivity, and oxidation reduction potential (ORP) of the eluate of the decanted eluate from the previous leaching interval (see Methods 9040, 9045, and 9050).

NOTE: Measurement of pH, conductivity, and ORP should be taken within 15 minutes of eluent exchange (Sec. 11.5) to avoid neutralization of the solution due to exposure to carbon dioxide, especially when alkaline materials are tested.

NOTE: The measurement of ORP is optional, but strongly recommended, especially when testing materials where oxidation is likely to change the chemistry of COPCs.

11.6.2 Filter the remaining eluate through a 0.45-µm membrane (Sec. 6.5).

11.6.3 Immediately preserve and store the volume(s) of eluate required for chemical analysis. Preserve all analytical samples in a manner that is consistent with the determinative chemical analyses to be performed.

11.6.4 Collect all subsequent eluate by repeating the eluent exchange and eluate processing procedures in Secs. 11.5 and 11.6.

12.0 DATA ANALYSIS AND CALCULATIONS

12.1 Data reporting

12.1.1 Figure 7 shows an example of a data sheet which may be used to report the concentration results of this method. At a minimum, the basic test report should include the following:

a) Name of the laboratory
b) Laboratory technical contact information
c) Date and time at the start of the test
d) Name or code of the solid material
e) Material description (including monolithic or compacted granular)
f) Moisture content of material used (g_{H_2O}/g)
g) Dimensions (cm) and geometry of sample used
h) Mass of solid material used (g)
i) Mass of sample and holder at start of test (g)
j) Eluate type (e.g., reagent water)
k) Eluate-specific information (see Sec. 12.1.2 below)

12.1.2 The minimum set of data that should be reported for each eluate includes:

a) Eluate sample ID
b) Target eluent exchange date and time
c) Actual eluent exchange date and time
d) Volume of eluent used (mL)
e) Mass of sample and holder (g)
f) Measured eluate pH

g) Measured eluate conductivity (mS/cm)
h) Measured ORP (mV) (optional)
i) Concentration of all COPCs
j) Analytical QC qualifiers as appropriate

12.2 Data presentation

12.2.1 Interval concentrations

12.2.1.1 At the conclusion of the schedule of leaching intervals (see Table 1), the concentration of COPCs in each eluate may be plotted as a function of cumulative leaching time. An example of this is shown in Figure 8 for mass transport from a monolithic field sample of fixated scrubber sludge and lime.

12.2.1.2 If data is available from Method 1313, interval concentrations and Method 1313 data may be plotted on the same graph as a function of eluate pH. This QC step is conducted in order to determine whether the concentration of COPCs approached equilibrium in any leaching interval (i.e., the driving force for mass transport from the matrix may not be constant, which is a common assumption of dynamic-tank leach testing). Figure 9 shows this type of graph for the release from a field sample of fixated scrubber sludge and lime.

12.2.2 Interval mass release

At the conclusion of the schedule of leaching intervals (see Table 1), the interval mass released can be calculated for each leaching interval as follows:

$$M_{t_i} = \frac{C_i \times V_i}{A}$$

Where: M_{t_i} = mass released during the current leaching interval, i (mg/m^2)

C_i = constituent concentration in the eluate for interval i (mg/L)
V_i = eluate volume in interval i (L)
A = specimen external geometric surface area exposed to the eluent (m^2)

12.2.3 Mean interval flux

The flux of a COPC in an interval may be plotted as a function of the generalized mean of the square root of cumulative leaching time ($\sqrt{t}$). An example of a flux graph is show in Figure 10 for the release from a field sample of fixated scrubber sludge with lime. This graph may be used to interpret the mechanism of release (see Ref. 5 for further details).

12.2.3.1 The flux across the exposed surface of the sample can be calculated by dividing the interval mass release by the interval duration as follows:

$$F_i = \frac{M_i}{t_i - t_{i-1}}$$

Where: F_i = flux for interval, i ($mg/m^2 \cdot s$)
M_i = mass released during the current leaching interval, i (mg/m^2)
t_i = cumulative time at the end of the current leaching interval, i (s)
t_{i-1} = cumulative time at the end of the previous leaching interval, i-1 (s)

12.2.3.2 The time used to plot each interval mass is the generalized mean of the square root of the cumulative leaching time using the cumulative time at the end of the i^{th} interval, t_i, and the cumulative time at the end of the previous interval, t_{i-1}.

$$\overline{t_i} = \left(\frac{\sqrt{t_i} + \sqrt{t_{i-1}}}{2} \right)^2$$

Where: $\overline{t_i}$ = generalized mean leaching time for the current interval, i (s)

t_i = cumulative time at the end of the current leaching interval, i (s)
t_{i-1} = cumulative time at the end of the previous leaching interval, i-1 (s)

NOTE: If the concentrations of a COPC in the eluates approach that shown in Method 1313 for liquid-solid equilibrium, the flux curve will show the pattern in Figure 10 with intervals of the same duration having the same flux value. When the eluate concentration approaches saturation, the driving force for mass transfer approaches zero, interval flux is limited, and intervals with like durations will display similar flux limitations.

12.2.4 Cumulative release

12.2.4.1 The interval release calculated in 12.2.2 can be summed to provide the cumulative mass release as a function of leaching time. Figure 11 shows the cumulative release curves for a field sample of fixated scrubber sludge with lime.

12.2.4.2 Interpretation of the cumulative release of constituents is illustrated using the analytical solution for simple radial diffusion from a cylinder into an infinite bath presented by Crank (see Ref. 8).

$$M_t = 2\rho C_o \left(\frac{D^{obs}\ t}{\pi} \right)^{1/2}$$

Where: M_t = cumulative mass released during leaching interval i (mg/m^2)
ρ = density of the "as-tested" sample (kg/m^3)
C_o = concentration of available COPC in the solid matrix (mg/kg)
D^{obs} = observed diffusivity (m^2/s)
t = leaching time (s)

When transformed to a log-log scale, the analytical solution presented by Crank becomes linear with the square root of time.

$$\log\left[M_t\right]=\log\left[2\rho C_o\left(\frac{D^{obs}}{\pi}\right)^{1/2}\right]+\frac{1}{2}t$$

Thus, under the assumptions of the analytical solution presented by Crank, the mass release should be proportional to the square root of time. A line showing the square root of time is plotted in Figure 11 along with the data. Since flux is the derivative of release, a similar treatment of flux as a function of leaching time using the simple diffusion model would be proportional to the negative square root of time as shown in Figure 10.

Models other than the simple diffusion model presented by Crank may also be used to interpret mass release. For example, the Shrinking Unreacted Core Model (see Ref. 2) and the Coupled Dissolution-Diffusion Model (see Ref. 7) incorporate chemical release parameters (e.g., as derived from Method 1313 data) into the model to better estimate release mechanisms and predictions (see Ref. 5 for further details).

12.2.5 Observed diffusivity

An observed diffusivity for each COPC can be determined using the logarithm of the cumulative release plotted versus the logarithm of time. In the case of a diffusion-controlled mechanism, this plot is expected to be a straight line with a slope of 0.5. An observed diffusivity can then be determined for each leaching interval where the slope is 0.50 ± 0.15 (see Ref. 1 and Ref. 14) by the following:

$$D_i^{obs}=\pi\left[\frac{M_{t_i}}{2\rho C_o\left(\sqrt{t_i}-\sqrt{t_{i-1}}\right)}\right]^2$$

Where: D_i^{obs} = observed diffusivity of a COPC for leaching interval i (m^2/s)

M_{t_i} = mass released during leaching interval i (mg/m^2)

t_i = cumulative contact time at the end of the current leaching interval, i (s)
t_{i-1} = cumulative contact time at the end of the previous leaching interval, i−1 (s)
ρ = sample density (dry basis) ($kg\text{-}dry/m^3$)
C_0 = initial leachable content (i.e., available release potential) (mg/kg)

The mean observed diffusivity for each COPC is then determined by taking the average of the interval observed diffusivities. It should be reported with the computed uncertainty (i.e., standard deviation).

NOTE: Since the analysis presented above assumes a diffusion process, only those interval mass transfer coefficients corresponding to leaching intervals with slopes of 0.50 ± 0.15 are included in the overall average mass-transfer coefficient.

12.3 Data representation by constituent

A concise representation of all relevant data for a single constituent may be presented as shown in Figure 12 for arsenic from a field core of fixated scrubber sludge with lime (FSSL) material. The data shows eluate pH generation as a function of leaching time (Figure 12a), comparison between eluate concentrations and Method 1313 data as a function of eluate pH (Figure 12b), constituent flux as a function of generalized mean cumulative leaching time (Figure 12c), and constituent release as a function of cumulative leaching time (Figure 12d).

12.4 Interpolation/extrapolation to target time values

The collected time dependence data may be interpolated or extrapolated to the nearest target cumulative time (Σt) value for purposes of comparing different data sets (e.g., test replicates of the same or different materials). The most transparent and straightforward method is linear interpolation/extrapolation of data after $\log_{10}$ transformation.

12.4.1 Log_{10} transformation

Collected concentration values are transformed by taking the $\log_{10}$ of the measured concentration at each test position, i:

$$\mathrm{C_i} = \log_{10}(\mathrm{c_i})$$

Where: C_i = $\log_{10}$-transformed concentration at test position i ($\log_{10}$[mg/L])
c_i = the concentration measured at test position i (mg/L)

12.4.2 Linear interpolation/extrapolation

Given a set of coordinate data sorted by increasing order according to Σt value (e.g., $\Sigma t_1 < \Sigma t_2 < \cdots < \Sigma t_n$), an interpolated/extrapolated $\log_{10}$-transformed concentration at a known Σt target is calculated as:

$$C_T = \mathrm{a_T} + \mathrm{b_T} \sum \mathrm{t_T}$$

Where: C_T = the concentration at target Σt value, Σt_T ($\log_{10}$[s])
a_T and b_T are coefficients of the linear interpolation/extrapolation equation
Σt_T = a target cumulative time value

Depending on the values of observed Σt values relative to target Σt values, the calculations of the coefficients a_T and b_T in the equation may differ according to the following algorithm:

- If $\Sigma t_T < \Sigma t_1$, then $b_T = (C_2 - C_1) / (\Sigma t_2 - \Sigma t_1)$ and $a_T = C_2 - b_T \cdot \Sigma t_2$ (extrapolation from the two points with closest Σt values)
- If $\Sigma t_T \geq \Sigma t_n$, then $b_T = (C_n - C_{n-1}) / (\Sigma t_n - \Sigma t_{n-1})$ and $a_T = C_n - b_T \cdot \Sigma t_n$ (extrapolation from the two points with closest Σt values)
- If $\Sigma t_{j-1} \leq \Sigma t_T < \Sigma t_j$, then $b_T = (C_j - C_{j-1}) / (\Sigma t_j - \Sigma t_{j-1})$ and $a_T = y_j - b_T \cdot \Sigma t_j$ (interpolation from the two closest points surrounding Σt_T)

NOTE: Interpolation or extrapolation of data should only be conducted within a distance of ±20% of the target Σt value. Since the allowable L/S tolerance about a target L/S value is variable (see Table 1), interpolation/extrapolation should not create data at a target Σt value where collected data is missing.

13.0 METHOD PERFORMANCE

13.1 Performance data and related information are provided in SW-846 methods only as examples and guidance. The data do not represent required performance criteria for users of the methods. Instead, performance criteria should be developed on a project-specific basis, and the laboratory should establish in-house QC performance criteria for the application of this method. Performance data must not be used as absolute QC acceptance criteria for laboratory QC or accreditation.

13.2 Interlaboratory validation of this method was conducted using a solidified waste analog (material code SWA) and a contaminated smelter site soil (material code CFS). Repeatability and reproducibility was determined for mean interval flux excluding the first wash-off interval (see Table 2) and for cumulative mass released after 63 days of leaching (see Table 3). More details on the interlaboratory validation may be found in Ref. 4.

13.3 Ref. 5 and Ref. 12 may provide additional guidance and insight on the use, performance, and application of this method.

14.0 POLLUTION PREVENTION

14.1 Pollution prevention encompasses any technique that reduces or eliminates the quantity and/or toxicity of waste at the point of generation. Numerous opportunities for pollution prevention exist in laboratory operations. The EPA has established a preferred hierarchy of environmental management techniques that places pollution prevention as the management option of first choice. Whenever feasible, laboratory personnel should use pollution prevention techniques to address their waste generation. When wastes cannot be feasibly reduced at the source, the Agency recommends recycling as the next best option.

14.2 For information about pollution prevention that may be applicable to laboratories and research institutions consult *Less is Better: Laboratory Chemical Management for Waste Reduction*, a free publication available from the ACS, Committee on Chemical Safety, https://www.acs.org/content/dam/acsorg/about/governance/committees/chemicalsafety/publications/less-is-better.pdf.

15.0 WASTE MANAGEMENT

The EPA requires that laboratory waste management practices be conducted consistent with all applicable rules and regulations. Laboratories are urged to protect air, water, and land by minimizing and controlling all releases from hoods and bench operations, complying with the letter and spirit of any sewer discharge permits and regulations, and by complying with all solid and hazardous waste regulations, particularly the hazardous waste identification rules and land disposal restrictions. For further information on waste management, consult *The Waste Management Manual for Laboratory Personnel* available at: http://www.labsafetyinstitute.org/FreeDocs/WasteMgmt.pdf.

16.0 REFERENCES

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17.0 TABLES, DIAGRAMS, FLOWCHARTS, AND VALIDATION DATA

The following pages contain the tables and figures referenced by this method.

TABLE 1

SCHEDULE OF ELUATE RENEWALS

Interval Label	Interval Duration (h)	Interval Duration (d)	Cumulative Leaching Time (d)
T01	2.0 ± 0.25	–	0.08
T02	23.0 ± 0.5	–	1.0
T03	23.0 ± 0.5	–	2.0
T04	–	5.0 ± 0.1	7.0
T05	–	7.0 ± 0.1	14.0
T06	–	14.0 ± 0.1	28.0
T07	–	14.0 ± 0.1	42.0
T08	–	7.0 ± 0.1	49.0
T09	–	14.0 ± 0.1	63.0

NOTE: This schedule may be extended for additional 14-day contact intervals to provide more information regarding longer-term release.

TABLE 2

METHOD PRECISON FOR MEAN INTERVAL FLUX (2^{nd} – 9^{th} Intervals)

Analyte	Symbol	Reapeatability – SWA $\%RSD_r$	Repeatability – CFS $\%RSD_r$	Reproducibility – SWA $\%RSD_R$	Reproducibility – CFS $\%RSD_R$
Aluminum	Al	7.3	13.3	25.3	25.3
Antimony	Sb	9.2	14.8	21.8	23.8
Arsenic	As	19.9	-	31.1	-
Barium	Ba	13.2	7.5	44.8	18.3
Boron	B	10.8	7.2	27.3	27.1
Cadmium	Cd	-	7.6	-	23.2
Calcium	Ca	8.1	6.6	28.7	26.0
Chromium	Cr	10.2	-	23.8	-
Lead	Pb	-	4.3	-	19.8
Potassium	K	12.4	10.8	28.8	40.1
Selenium	Se	10.9	13.3	30.8	32.4
Vanadium	V	8.5	11.3	22.3	30.6

Material	Reapeatability – SWA $\%RSD_r$	Repeatability – CFS $\%RSD_r$	Repeatability – Overall	Reproducibility – SWA $\%RSD_R$	Reproducibility – CFS $\%RSD_R$	Reproducibility – Overall
Mean	11%	10%	11%	29%	27%	28%

NOTE: First interval is removed from mean interval flux because of variances associated with wash-off of surface contaminants that do not pertain to the method precision.

Data taken from Ref. 4.

TABLE 3

METHOD PRECISON FOR CUMULATIVE RELEASE AFTER 63 DAYS

Analyte	Symbol	Repeatability – SWA %RSD_r	Repeatability – CFS %RSD_r	Reproducibility – SWA %RSD_R	Reproducibility – CFS %RSD_R
Aluminum	Al	5.4	5.3	23.6	22.9
Antimony	Sb	6.9	5.9	19.7	14.4
Arsenic	As	15.9	-	31.0	-
Barium	Ba	7.5	3.9	35.6	16.5
Boron	B	8.4	3.7	22.6	25.7
Cadmium	Cd	-	4.8	-	18.4
Calcium	Ca	4.6	3.2	23.9	24.6
Chromium	Cr	7.7	-	17.7	-
Lead	Pb	-	1.6	-	12.0
Potassium	K	10.8	6.3	24.8	44.4
Selenium	Se	8.7	3.6	26.7	20.5
Vanadium	V	5.7	4.2	21.1	22.8

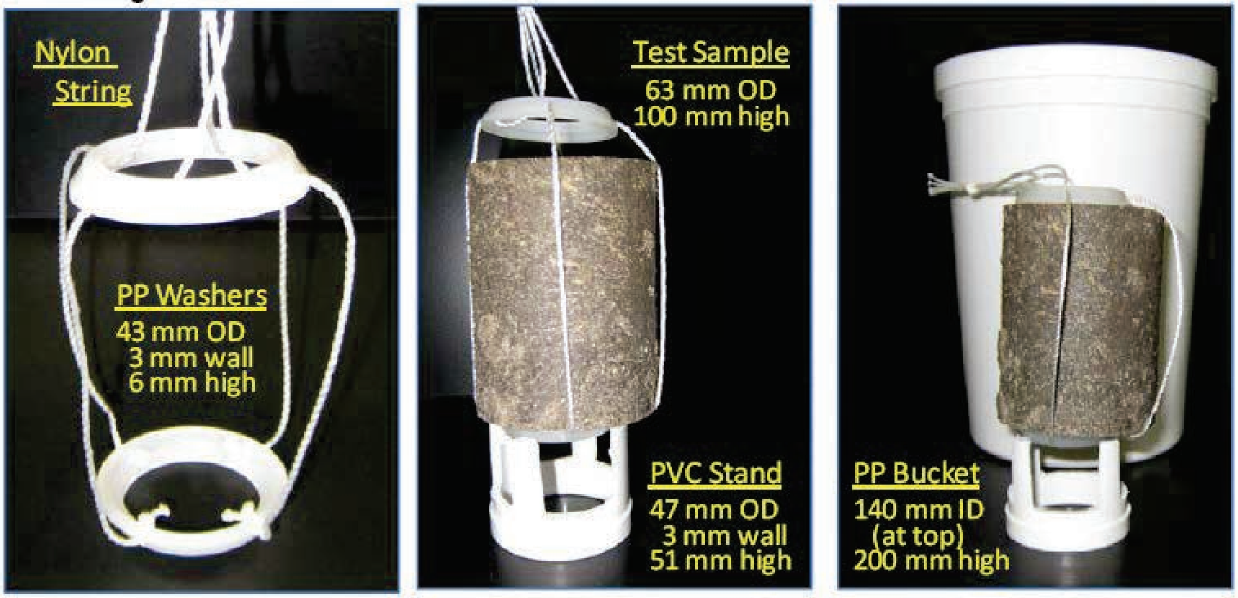
Material	Repeatability – SWA %RSD_r	Repeatability – CFS %RSD_r	Repeatability – Overall	Reproducibility – SWA %RSD_R	Reproducibility – CFS %RSD_R	Reproducibility – Overall
Mean	8%	4%	6%	25%	22%	23%

Data taken from Ref. 4.

FIGURE 1

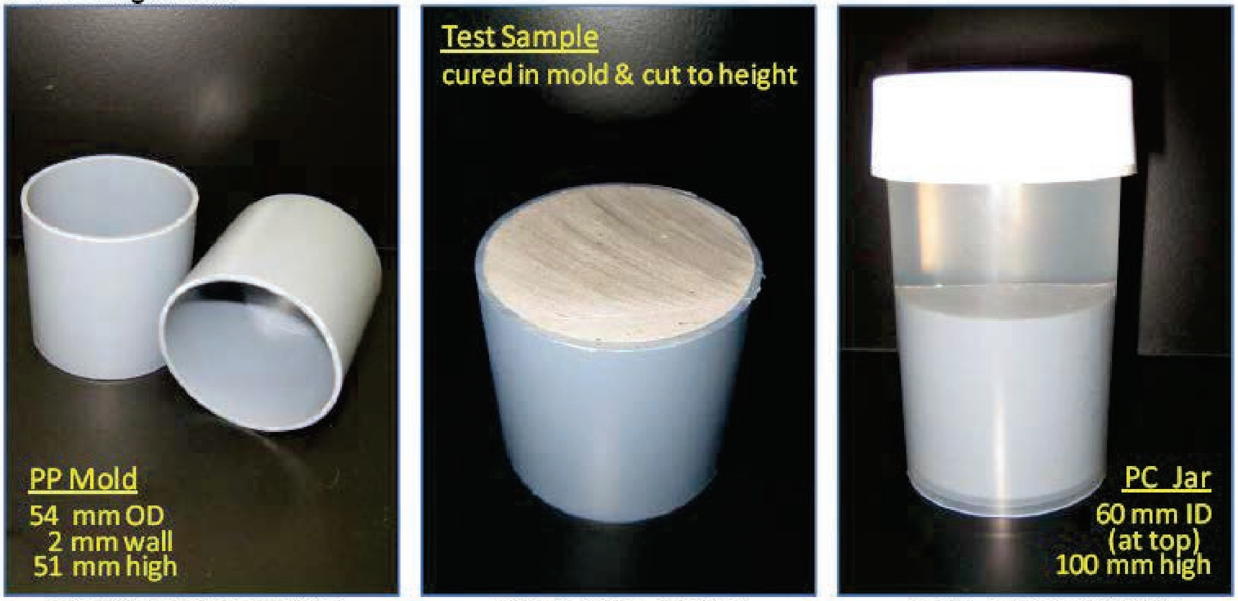
EXAMPLES OF MONOLITHIC SAMPLE HOLDERS

3-D Configuration



Sample Holder | Sample, Holder and Stand | 3-D Leaching Setup

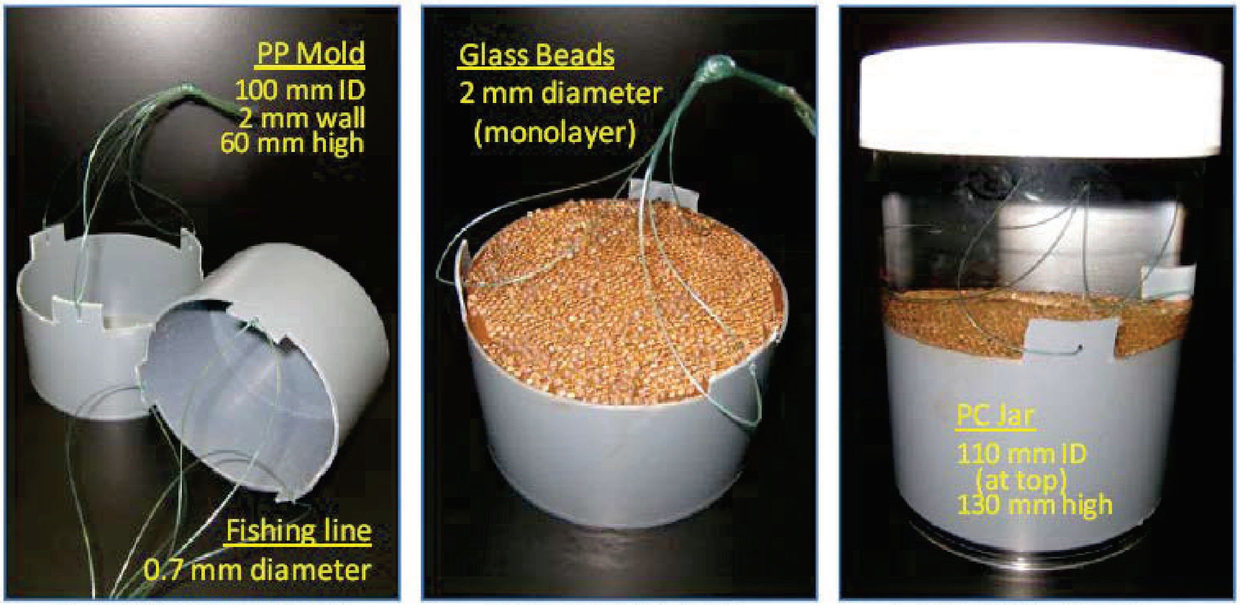
1-D Configuration



Empty Sample Holder | Full Sample Holder | 1-D Leaching Setup

FIGURE 2

EXAMPLE COMPACTED GRANULAR SAMPLE HOLDER AND SETUP



Empty Sample Holder Compacted Sample 1-D Leaching Setup

FIGURE 3

METHOD FLOWCHART

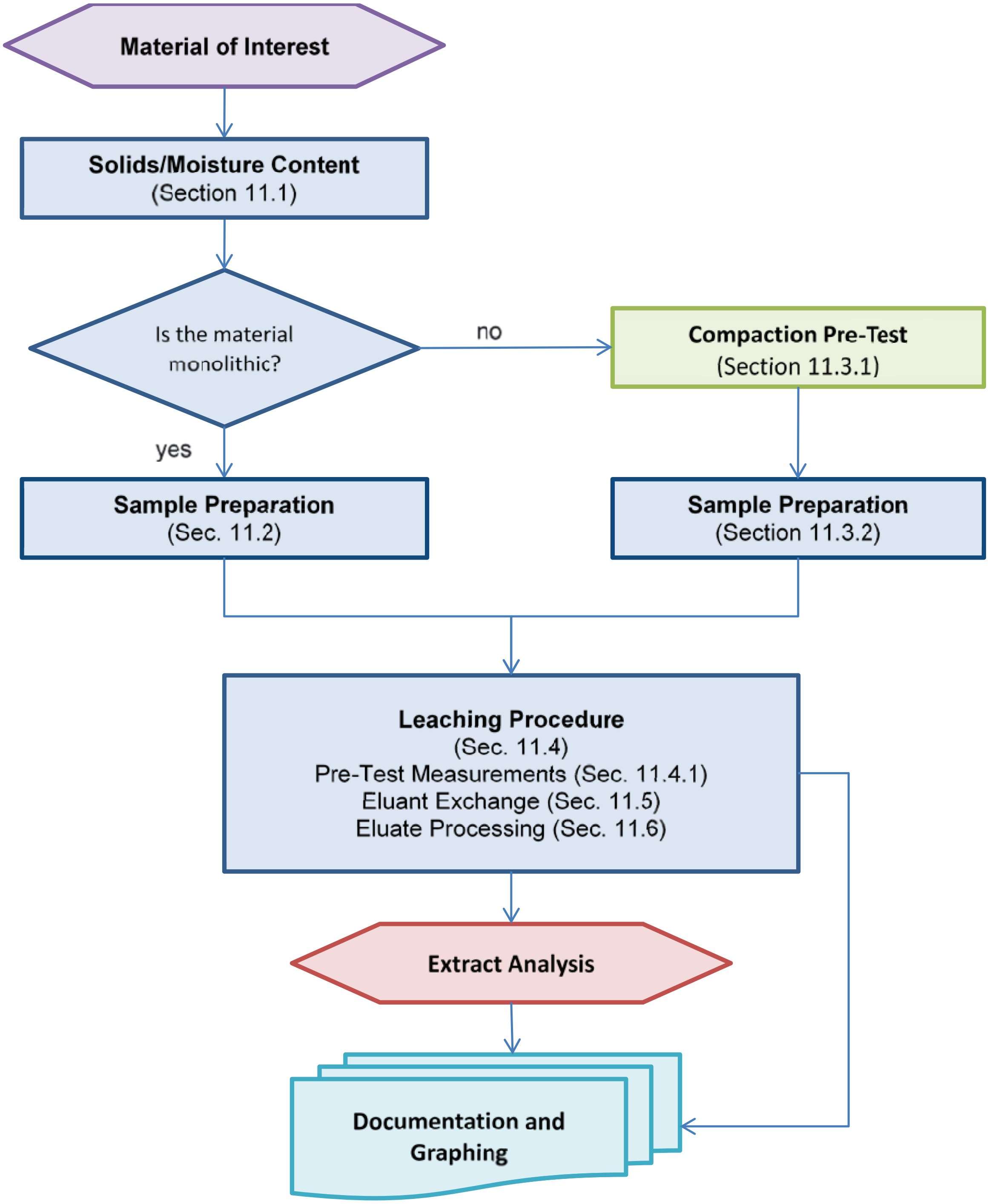


FIGURE 4

EXAMPLE CURVE OF PACKING DENSITY AS A FUNCTION OF MOISTURE CONTENT

$y = 55.975x^3 – 65.036x^2 + 1.8352$

$r^2 = 0.983$

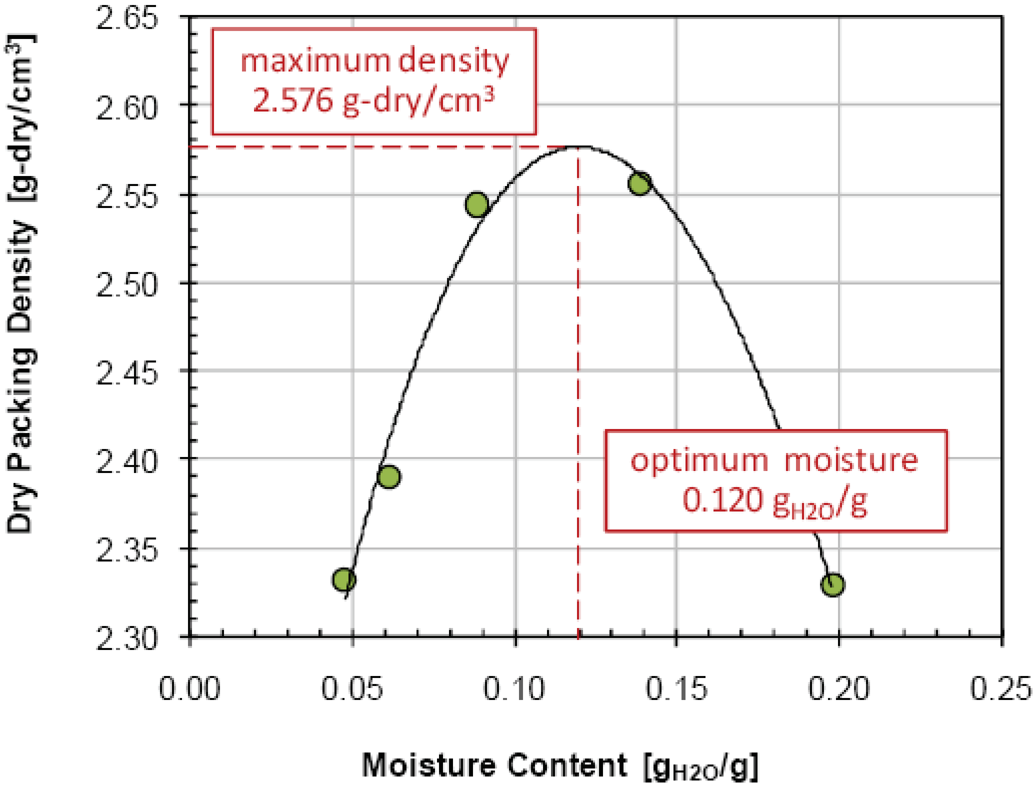


FIGURE 5

SCHEMATIC OF SEMI-DYNAMIC MASS TRANSFER TEST PROCESS

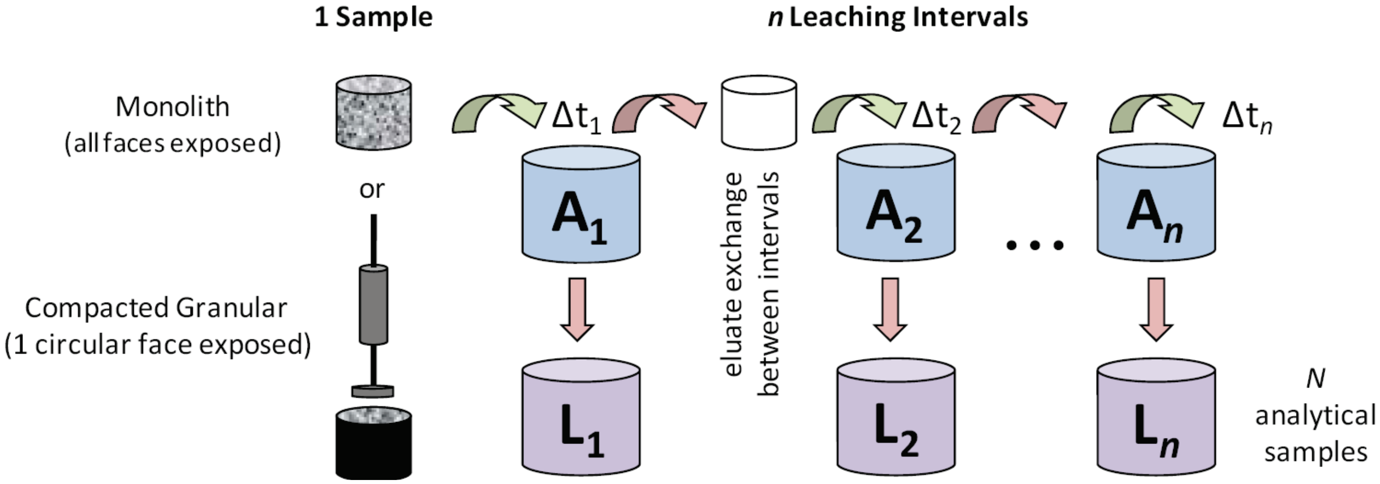
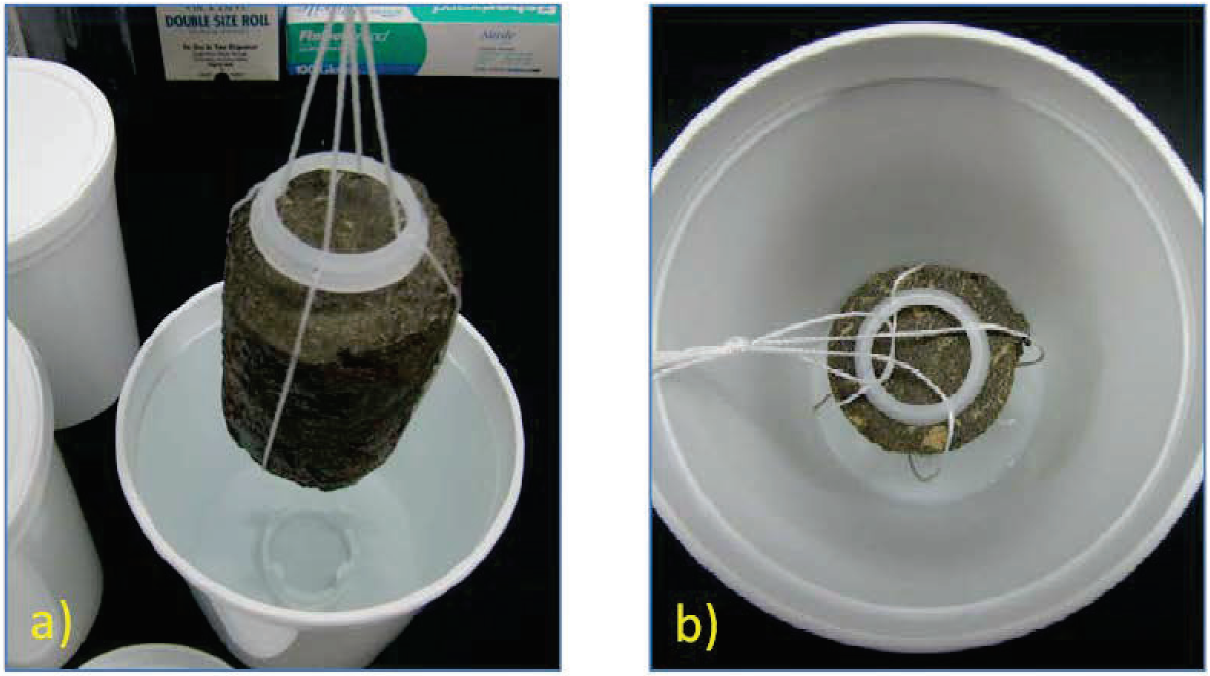


Figure obtained and modified from Ref. 1.

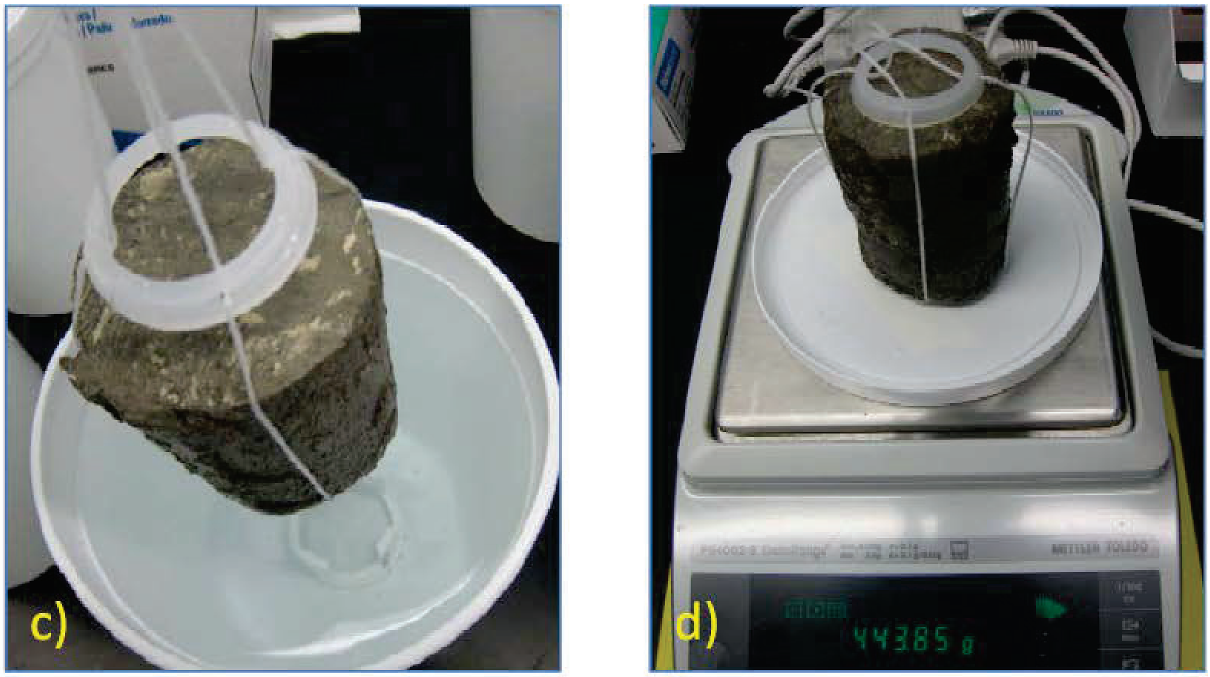
FIGURE 6

EXAMPLE LEACHING PROCEDURE STEPS



Start of Leaching Interval

Sample Centered in Eluant (top view)

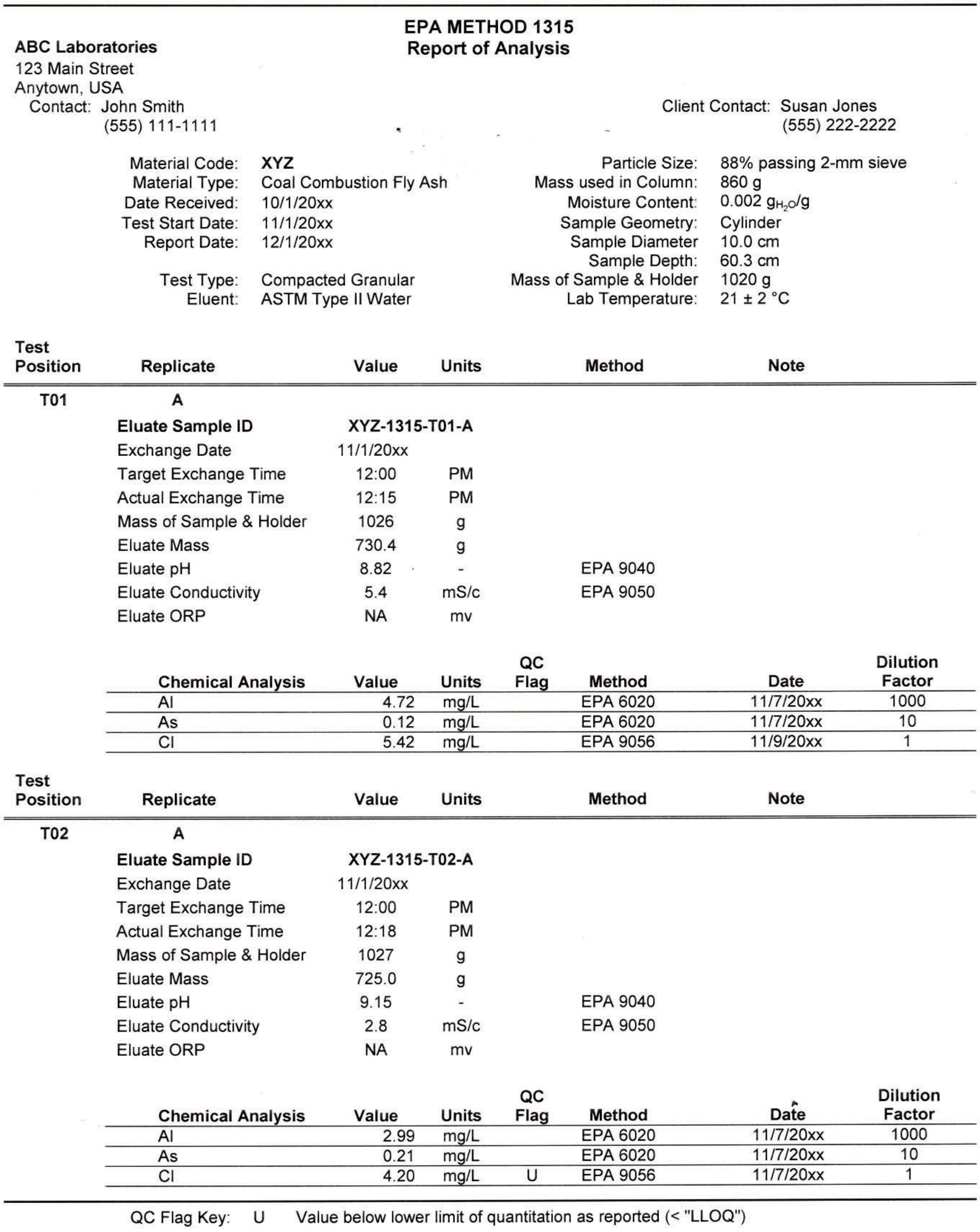


Removing Sample for Exchange

Mass of Sample and Holder

FIGURE 7

EXAMPLE DATA REPORTING FORMAT



EPA METHOD 1315
Report of Analysis

ABC Laboratories
123 Main Street
Anytown, USA
Contact: John Smith
(555) 111-1111

Client Contact: Susan Jones
(555) 222-2222

Material Code: **XYZ**
Material Type: Coal Combustion Fly Ash
Date Received: 10/1/20xx
Test Start Date: 11/1/20xx
Report Date: 12/1/20xx

Test Type: Compacted Granular
Eluent: ASTM Type II Water

Particle Size: 88% passing 2-mm sieve
Mass used in Column: 860 g
Moisture Content: 0.002 g_{H_2O}/g
Sample Geometry: Cylinder
Sample Diameter 10.0 cm
Sample Depth: 60.3 cm
Mass of Sample & Holder 1020 g
Lab Temperature: 21 ± 2 °C

Test Position	**Replicate**	**Value**	**Units**	**Method**	**Note**
T01	**A**				
	Eluate Sample ID	**XYZ-1315-T01-A**			
	Exchange Date	11/1/20xx			
	Target Exchange Time	12:00	PM		
	Actual Exchange Time	12:15	PM		
	Mass of Sample & Holder	1026	g		
	Eluate Mass	730.4	g		
	Eluate pH	8.82	-	EPA 9040	
	Eluate Conductivity	5.4	mS/c	EPA 9050	
	Eluate ORP	NA	mv		

Chemical Analysis	**Value**	**Units**	**QC Flag**	**Method**	**Date**	**Dilution Factor**
Al	4.72	mg/L		EPA 6020	11/7/20xx	1000
As	0.12	mg/L		EPA 6020	11/7/20xx	10
Cl	5.42	mg/L		EPA 9056	11/9/20xx	1

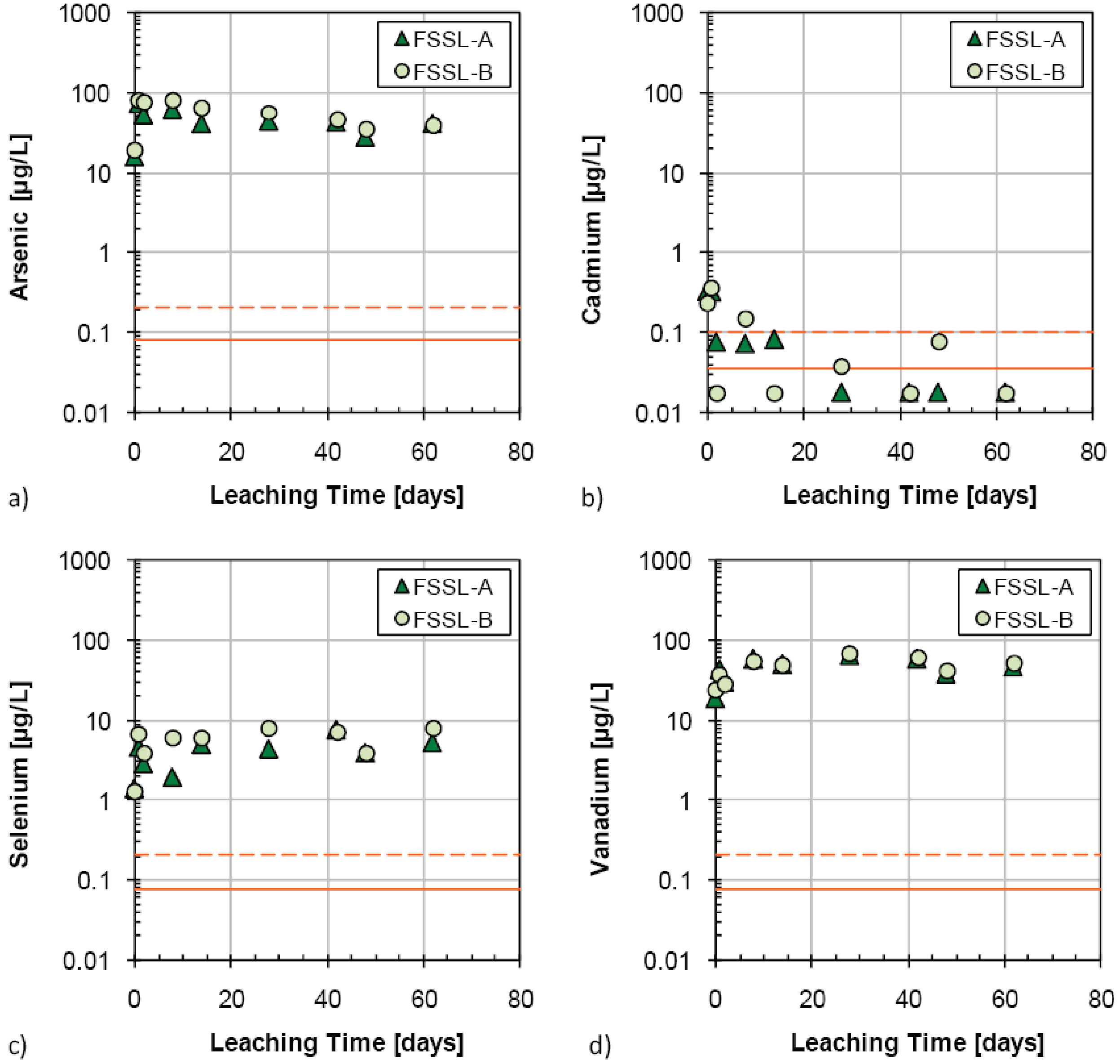
Test Position	**Replicate**	**Value**	**Units**	**Method**	**Note**
T02	**A**				
	Eluate Sample ID	**XYZ-1315-T02-A**			
	Exchange Date	11/1/20xx			
	Target Exchange Time	12:00	PM		
	Actual Exchange Time	12:18	PM		
	Mass of Sample & Holder	1027	g		
	Eluate Mass	725.0	g		
	Eluate pH	9.15	-	EPA 9040	
	Eluate Conductivity	2.8	mS/c	EPA 9050	
	Eluate ORP	NA	mv		

Chemical Analysis	**Value**	**Units**	**QC Flag**	**Method**	**Date**	**Dilution Factor**
Al	2.99	mg/L		EPA 6020	11/7/20xx	1000
As	0.21	mg/L		EPA 6020	11/7/20xx	10
Cl	4.20	mg/L	U	EPA 9056	11/7/20xx	1

QC Flag Key: U Value below lower limit of quantitation as reported (< "LLOQ")

FIGURE 8

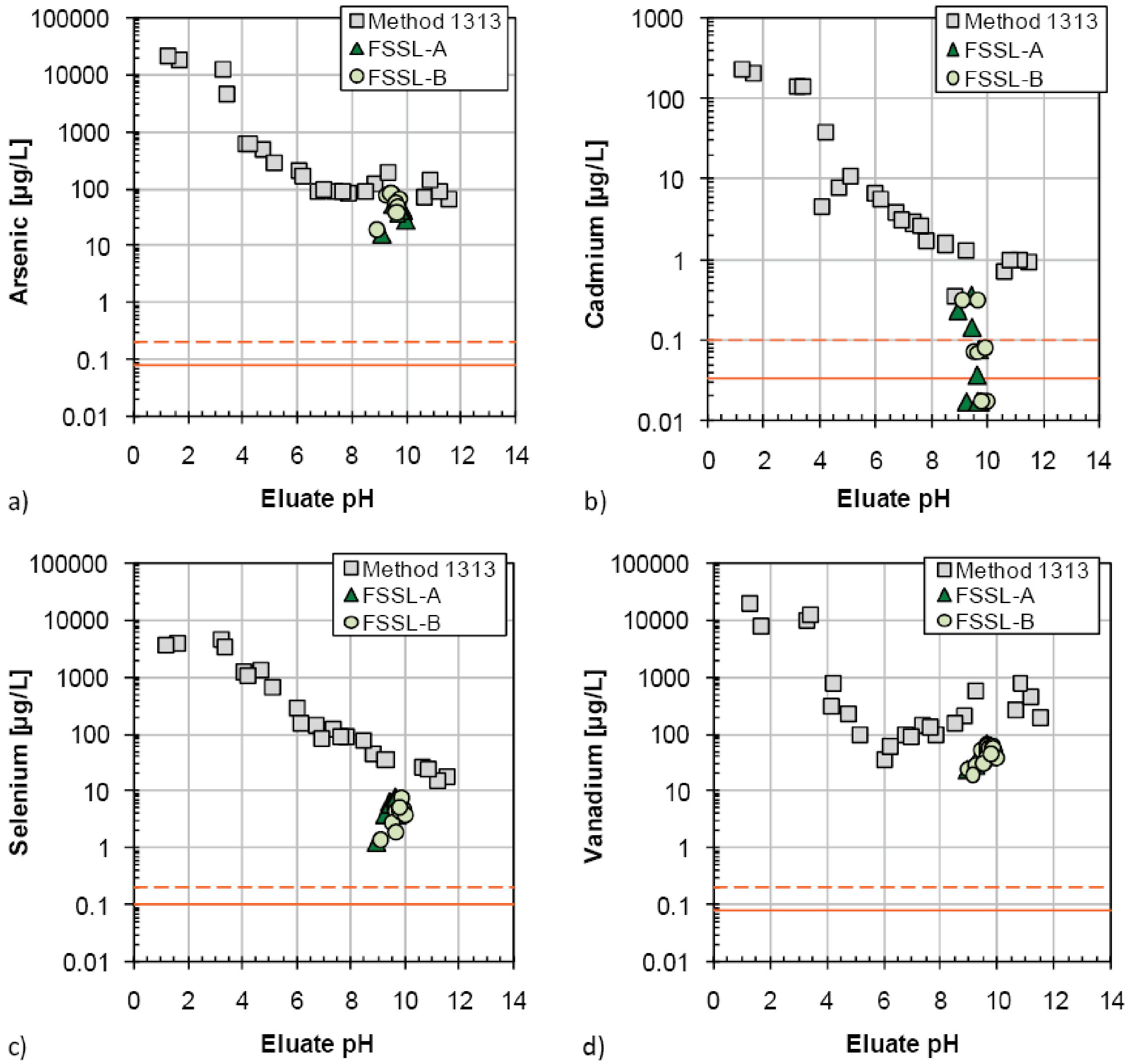
EXAMPLE INTERVAL CONCENTRATION GRAPHS



NOTE: Orange lines represent cumulative release if all eluate extracts were at the quantitation limit (dashed) and detection limit (solid). Chemical analyses below the detection limit are shown at ½ the detection limit value.

FIGURE 9

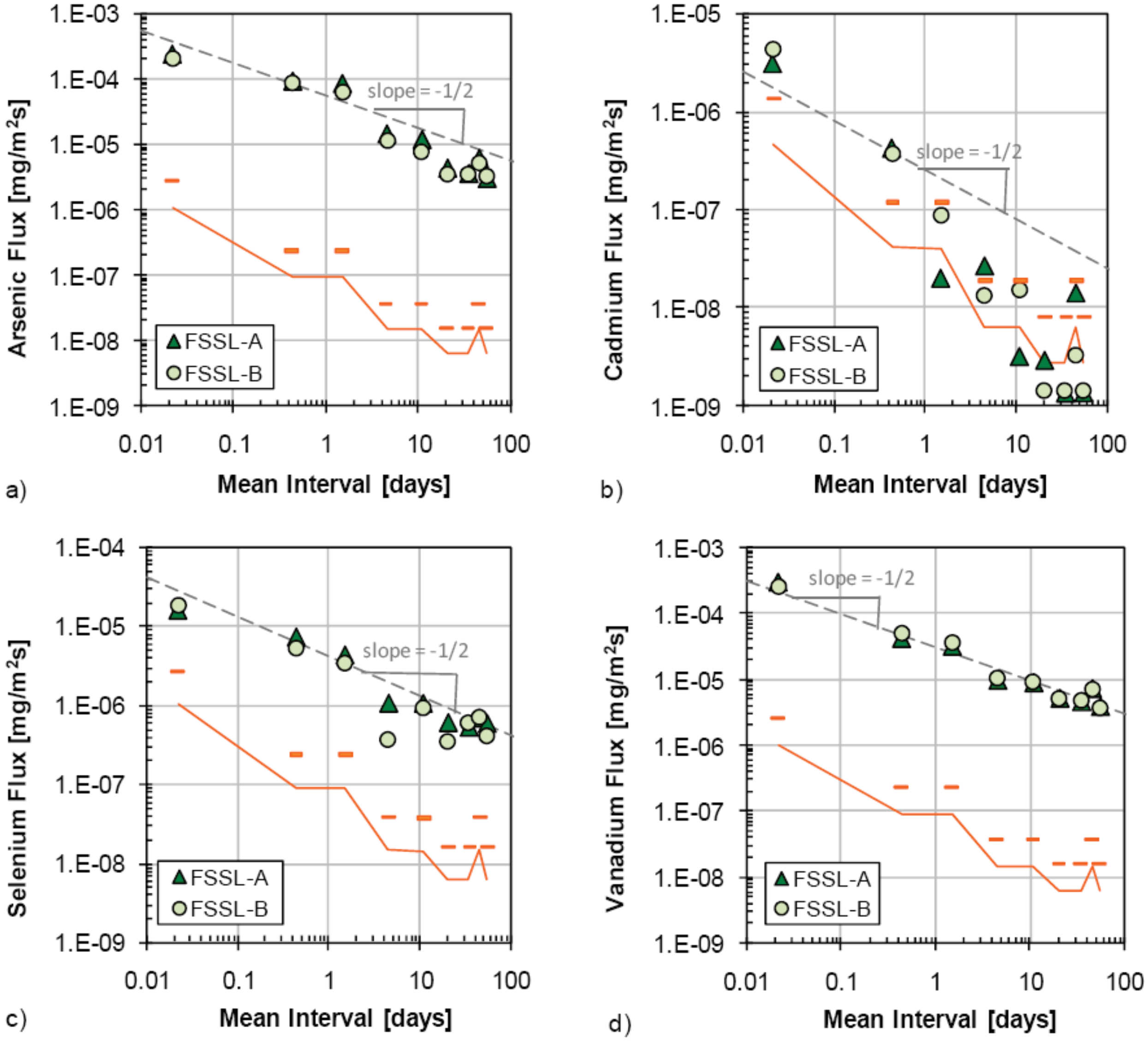
EXAMPLE OF SATURATION CHECK BETWEEN INTERVAL CONCENTRATIONS AND METHOD 1313 DATA



NOTE: Orange lines represent cumulative release if all eluate extracts were at the quantitation limit (dashed) and detection limit (solid). Chemical analyses below the detection limit are shown at ½ the detection limit value.

FIGURE 10

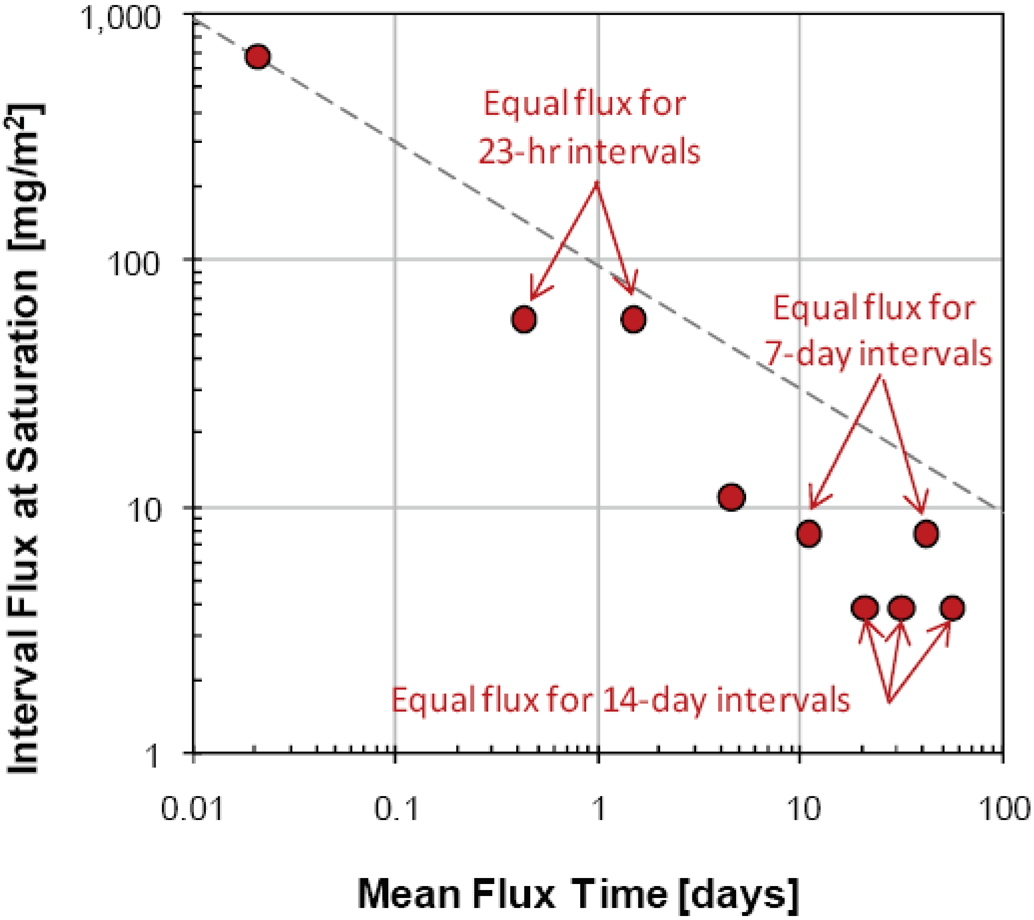
EXAMPLE INTERVAL FLUX GRAPHS



<u>NOTE</u>: Orange data represent cumulative release if all eluate extracts were at the quantitation limit (dashes) and detection limit (solid line).

FIGURE 11

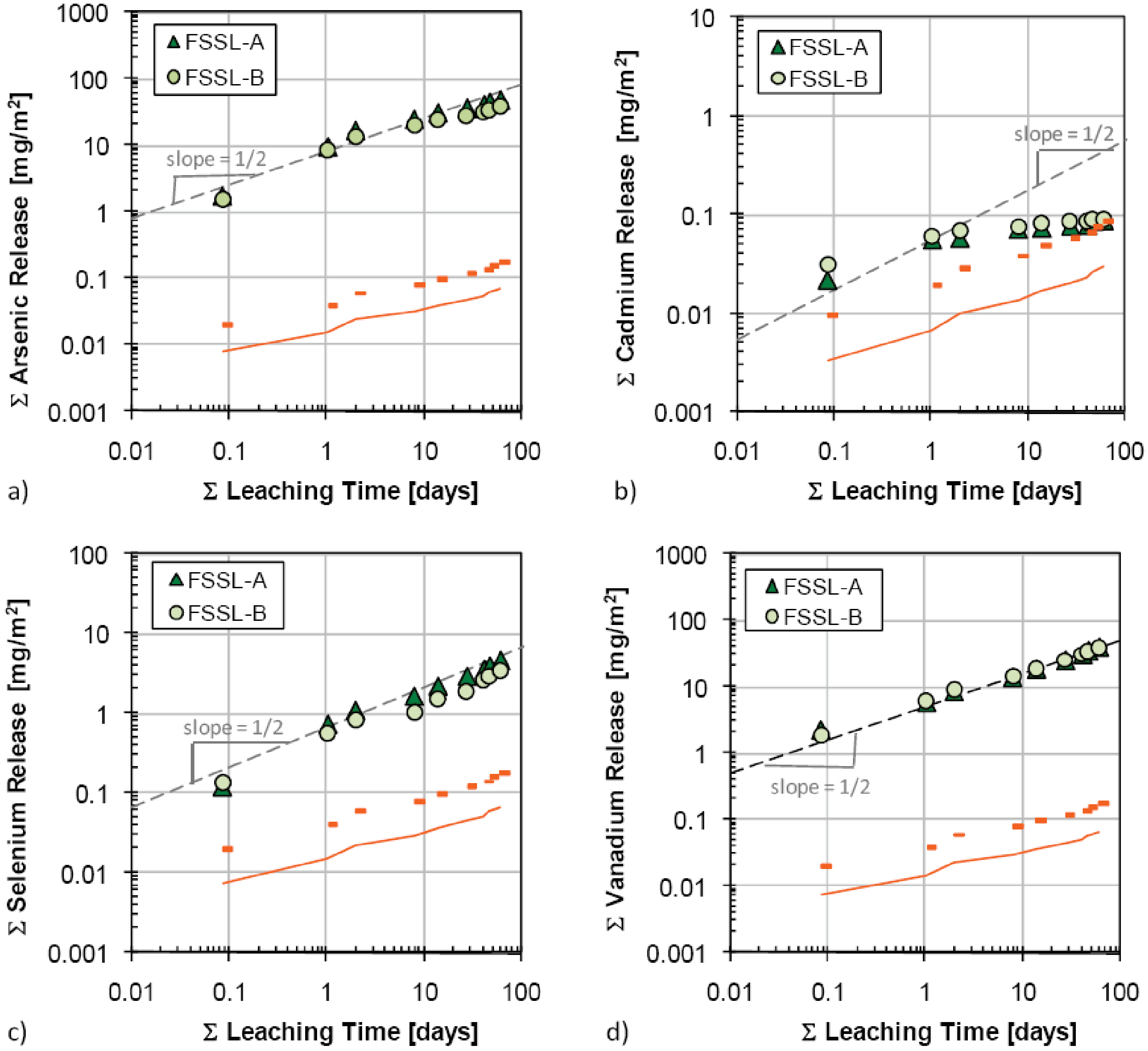
INTERVAL FLUX AT ELUATE SATURATION



NOTE: This figure assumes that the concentration in the eluate approaches saturation during the leaching interval (i.e., the driving force for diffusion approaches zero). When the leaching solution is saturated, the resulting mass release and interval flux is constant for intervals of the same duration.

FIGURE 12

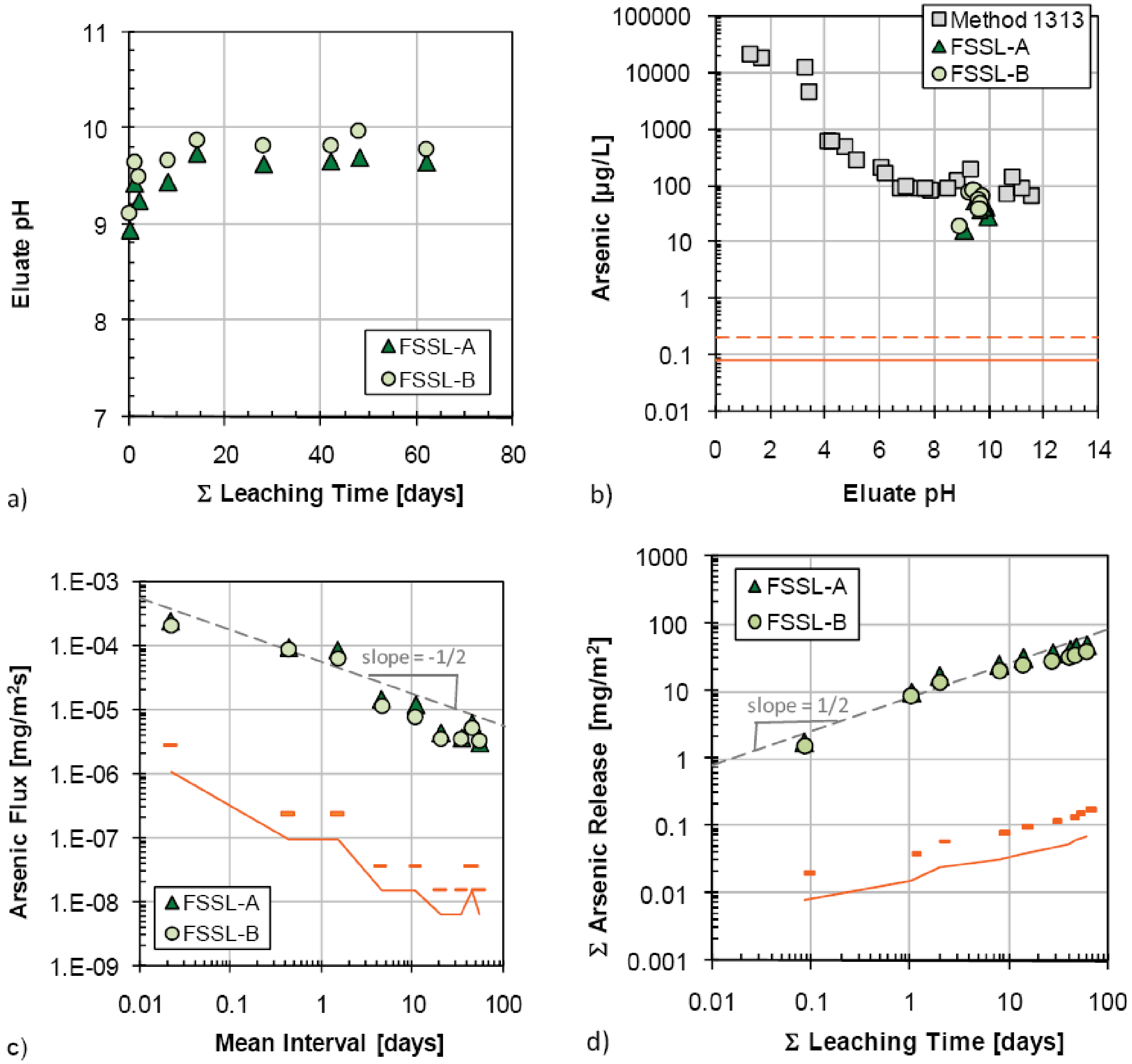
EXAMPLE CUMULATIVE RELEASE GRAPHS



NOTE: Orange data represent cumulative release if all eluate extracts were at the quantitation limit (dashes) and detection limit (solid line).

FIGURE 13

DATA REPRESENTATION BY CONSTITUENT (QUAD FORMAT)



<u>NOTE</u>: Orange data represent cumulative release if all eluate extracts were at the quantitation limit (dashes) and detection limit (solid line).

DOCUMENT

6

METHOD 1316[1]

LIQUID-SOLID PARTITIONING AS A FUNCTION OF LIQUID-TO-SOLID RATIO IN SOLID MATERIALS USING A PARALLEL BATCH PROCEDURE

SW-846 is not intended to be an analytical training manual. Therefore, method procedures are written based on the assumption that they will be performed by analysts who are formally trained in at least the basic principles of chemical analysis and in the use of the subject technology.

In addition, SW-846 methods, with the exception of required methods used for the analysis of method-defined parameters, are intended to be guidance methods that contain general information on how to perform an analytical procedure or technique, which a laboratory can use as a basic starting point for generating its own detailed standard operating procedure (SOP), either for its own general use or for a specific project application. Performance data included in this method are for guidance purposes only and must not be used as absolute quality control (QC) acceptance criteria for purposes of laboratory QC or accreditation.

TABLE OF CONTENTS

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[1] This method has been derived from the SR003 procedure (Ref. 4) using Environmental Protection Agency-reviewed and accepted methodologies (see Ref. 3, Ref. 6, and Ref. 7). The method is analogous to batch L/S-dependence method EN12457 (Ref. 5) developed for the Comité Européen de Normalisation (CEN).

1.0 SCOPE AND APPLICATION

1.1 This method is designed to provide the liquid-solid partitioning (LSP) of inorganic constituents (e.g., metals, radionuclides) and non-volatile organic constituents (e.g., polycyclic aromatic hydrocarbons (PAHs)), dissolved organic carbon) at the natural pH of the solid material as a function of liquid-to-solid ratio (L/S) under conditions that approach liquid-solid chemical equilibrium. Table 1 shows the range of target L/S values tested under this method.

1.2 The eluate concentrations at a low L/S provide insight into pore solution composition either in a granular bed (e.g., soil column) or in the pore space of low-permeability material (e.g., solidified monolithic or compacted granular fill). In addition, analysis of eluates for dissolved organic carbon and of the solid phase for total organic carbon allow for evaluation of the impact of organic carbon release and the influence of dissolved organic carbon on the LSP of inorganic constituents.

1.3 This method is intended to be used as part of environmental leaching assessment for the evaluation of disposal, beneficial use, treatment effectiveness and site remediation. The method is not required by federal regulations to determine whether waste passes or fails the toxicity characteristic as defined at 40 CFR 261.24.

1.4 This method is suitable for assessing the leaching potential of a wide range of solid materials. Examples of solid materials include: industrial wastes, soils, sludges, combustion residues, sediments, stabilized materials, construction materials, and mining wastes.

1.5 This method is a leaching characterization method used to provide intrinsic material parameters that control leaching of inorganic species under equilibrium conditions. This test method is intended as a means for obtaining an extract (i.e., the eluate) of a solid material which may be used to estimate the solubility and release of inorganic constituents under the laboratory conditions described in this method. Extract concentrations may be used in conjunction with information regarding environmental management scenarios to estimate anticipated leaching concentrations, and release rate and extent for individual material constituents in the management scenarios evaluated. Extract concentrations may also be used along with geochemical speciation modeling to infer the mineral phases that control the LSP in the pore structure of the solid material.

1.6 This method is not applicable to characterize the release of volatile organic analytes (e.g., benzene, toluene and xylenes).

1.7 This method provides solutions that are considered to be indicative of leachate under field conditions only where the field leaching pH and L/S ranges are encompassed by the laboratory extract final conditions and the LSP is controlled by aqueous-phase saturation of the constituent of interest. When LSP is controlled by the amount of the constituent present in the solid that may dissolve (i.e., for highly soluble species), the mass released (mg/kg), rather than the concentration, is indicative of field conditions.

1.8 The solvent used in this method is reagent water.

1.9 Analysts are advised to take reasonable measures to ensure that the sample is homogenized to the extent practical prior to employment of this method. Particle size reduction may provide additional assurance of sample homogenization. Table 2 designates a minimum dry equivalent mass of sample to be added to each extraction vessel and the associated extraction contact time as a function maximum particle diameter. If the heterogeneity of the sample is suspected as the cause of unacceptable levels of precision in replicate test results or is considered significant based on professional judgment, the sample mass used in the test procedure may be increased to a greater minimum dry equivalent mass than shown in Table 1 with the amount of extractant increased proportionately to maintain the designated L/S.

1.10 In the preparation of solid materials for use in this method, particle size reduction of samples with large grain size is used to enhance the approach towards liquid-solid equilibrium under the designated contact time interval of the extract process. The extract contact time for samples reduced to a finer maximum particle size will be shorter.

1.11 Prior to employing this method, analysts are advised to consult the base method for each type of procedure that may be employed in the overall analysis (e.g., Methods 9040, 9045, and 9050) for additional information on QC procedures, development of QC acceptance criteria, calculations, and general guidance. Analysts also should consult the disclaimer statement at the front of the manual and the information in Chapter Two for: 1) guidance on the intended flexibility in the choice of methods, apparatus, materials, reagents, and supplies, and 2) the responsibilities of the analyst for demonstrating that the techniques employed are appropriate for the analytes of interest, in the matrix of interest, and at the levels of concern.

In addition, analysts and data users are advised that, except where explicitly specified in a regulation, the use of SW-846 methods is not mandatory in response to federal testing requirements. The information contained in this method is provided by the Environmental Protection Agency (EPA or the Agency) as guidance to be used by the analyst and the regulated community in making judgments necessary to generate results that meet the data quality objectives (DQOs) for the intended application.

1.12 This method is restricted to use by, or under supervision of, properly experienced and trained personnel. Each analyst must demonstrate the ability to generate acceptable results with this method.

2.0 SUMMARY OF METHOD

This method consists of five parallel extractions of a particle size-reduced solid material in reagent water over a range of L/S values from 0.5 to 10 mL eluent/g dry material (see Table 1). In addition to the five test extractions, a method blank without solid sample is carried through the procedure in order to verify that analyte interferences are not introduced as a consequence of reagent impurities or equipment contamination. If multiple materials or replicate tests are carried out in parallel, only one set of method blanks is necessary. In total, six bottles (i.e., five test positions and one method blank) are tumbled in an end-over-end fashion for a specified contact time based on the maximum particle size of the solid (see Table 2). At the end of the contact interval, the liquid and solid phases are roughly separated via settling or centrifugation. Extract pH and specific conductance measurements are then taken on an aliquot of the liquid phase. The bulk of the eluate is clarified by pressure or vacuum filtration in preparation for constituent analysis. Analytical aliquots of the extracts are collected and preserved accordingly based on the determinative methods to be performed. The eluate constituent concentrations are plotted as a function of L/S and compared to QC and assessment limits.

3.0 DEFINITIONS

3.1 Constituent of potential concern (COPC) – A chemical species of interest, which may or may not be regulated, but may be characteristic of release-controlling properties of the sample geochemistry.

3.2 Release – The dissolution or partitioning of a COPC from the solid phase to the aqueous phase during laboratory testing (or under field conditions). In this method, mass release is expressed in units of mg COPC/kg dry solid material.

3.3 Liquid-solid partitioning (LSP) – The distribution of COPCs between the solid and liquid phases at the conclusion of the extraction.

3.4 Liquid-to-solid ratio (L/S) – The fraction of the total liquid volume (including the moisture contained in the "as used" solid sample) to the dry mass equivalent of the solid material. L/S is typically expressed in volume units of liquid per dry mass of solid material (mL/g-dry).

3.5 "As-tested" sample – The solid sample at the conditions (e.g., moisture content and particle-size distribution) present at the time of the start of the test procedure. The "as-tested" conditions will differ from the "as-received" sample conditions if particle-size reduction and drying were necessarily performed.

3.6 Dry-mass equivalent – The mass of "as-tested" (i.e., "wet") sample that equates to the mass of dry solids plus associated moisture, based on the moisture content of the "as-tested" material. The dry-mass equivalent is typically expressed in mass units of the "as-tested" sample (g).

3.7 Eluent – The solution used to contact the solid material in a leaching test. The eluent is usually free of COPCs but may contain other species used to control the test conditions of the extraction.

3.8 Eluate – The solution collected as an extract from a leaching test that contains the eluent plus constituents leached from the solid phase.[2]

3.9 Refer to Chapter One, Chapter Three, and the manufacturers' instructions for definitions that may be relevant to this procedure.

4.0 INTERFERENCES

Solvents, reagents, glassware, and other sample processing hardware may yield artifacts and/or interferences to sample analysis. All of these materials must be demonstrated to be free from interferences under the conditions of the analysis by analyzing method blanks. Specific selection of reagents may be necessary. Refer to each method to be used for specific guidance on QC procedures

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[2] The definition of "eluate" is used in this method to differentiate the output solution of a leaching test from the "leachate" solution collected from, or measured in, the field. The distinction between terms is made to minimize confusion when comparing laboratory results to field data (Ref. 5).

and to Chapters Three and Four for general guidance on glassware cleaning. Also refer to Methods 9040, 9045, and 9050 for a discussion of interferences.

5.0 SAFETY

This method does not address all safety issues associated with its use. The laboratory is responsible for maintaining a safe work environment and a current awareness file of Occupational Safety and Health Administration (OSHA) regulations regarding the safe handling of the chemicals specified in this method. A reference file of material safety data sheets (MSDSs) should be available to all personnel involved in these analyses.

6.0 EQUIPMENT AND SUPPLIES

The mention of trade names or commercial products in this manual is for illustrative purposes only, and does not constitute an EPA endorsement or exclusive recommendation for use. The products and instrument settings cited in SW-846 methods represent those products and settings used during the method development or subsequently evaluated by the Agency. Glassware, reagents, supplies, equipment, and settings other than those listed in this manual may be employed provided that method performance appropriate for the intended application has been demonstrated and documented.

This section does not list all common laboratory glassware (e.g., beakers and flasks) that might be used.

6.1 Extraction vessels

6.1.1 Six wide-mouth bottles (i.e., five for test positions plus one for a method blank) constructed of inert material, resistant to high and low pH conditions and interaction with the constituents of interest, as described in the following sections.

6.1.1.1 For the evaluation of inorganic COPCs, bottles made of high density polyethylene (HDPE) (e.g., Nalgene #3140-0250 or equivalent), polypropylene (PP), or polyvinyl chloride (PVC) are recommended.

6.1.1.2 For the evaluation of non-volatile organic and mixed organic/inorganic COPCs, bottles made of glass or Type-316 stainless steel are recommended. Polytetrafluoroethene (PTFE) is not recommended for non-volatile organics, due to the sorption of species with high hydrophobicity (e.g., PAHs). Borosilicate glass is recommended over other types of glass, especially when inorganic analytes are of concern.

6.1.2. The extraction vessels must be of sufficient volume to accommodate both the solid sample and an extractant volume based on the schedule of L/S values shown in Table 1. For example, a 500-mL bottle is recommended when 100 g dry equivalent mass is contacted with 200 mL of eluent (see T03 in Table 1).

6.1.3 The vessels must have a leak-proof seal that can sustain end-over-end tumbling for the duration of the designated contact time.

6.1.4 If centrifugation is anticipated to be beneficial for initial phase separation, the extraction vessels should be capable of withstanding centrifugation at 4000 ± 100 rpm for a minimum of 10 ± 2 min. Alternately, samples may be extracted in bottles that do not meet this centrifugation specification (e.g., Nalgene I-Chem #311-0250 or equivalent) and the solid-liquid slurries transferred into appropriate centrifugation vessels for phase separation as needed.

6.2 Balance – Capable of 0.01 g resolution for masses less than 500 g

6.3 Rotary tumbler – Capable of rotating the extraction vessels end-over-end at a constant speed of 28 ± 2 rpm (e.g., Environmental Express, Charleston, SC or equivalent)

NOTE: The holding capacity of tumblers may vary and modifications (e.g., packing or bottle-holding inserts) may be necessary to accommodate the extraction vessels.

6.4 Filtration apparatus – Pressure or vacuum filtration apparatus composed of appropriate materials to maximize collection of extracts and minimize loss of COPCs (e.g., Nalgene #300-4000 or equivalent) (see Sec. 6.1)

6.5 Filtration membranes – Composed of polypropylene or equivalent material with an effective pore size of 0.45 µm (e.g., Gelman Sciences GH Polypro #66548 from Fisher Scientific or equivalent)

6.6 pH meter – Laboratory model capable of temperature compensation (e.g., Accumet 20, Fisher Scientific or equivalent) with a minimum resolution of 0.1 pH units

6.7 pH combination electrode – Composed of chemically resistant materials

6.8 Conductivity meter – Laboratory model (e.g., Accumet 20, Fisher Scientific or equivalent), with a minimum resolution of 5% of the measured value

6.9 Conductivity electrodes – Composed of chemically resistant materials

6.10 Adjustable-volume pipettor – Oxford Benchmate series or equivalent.

The necessary delivery range will depend on the buffering capacity of the solid material and acid/base strength used in the test.

6.11 Disposable pipettor tips

6.12 Centrifuge (recommended) – Capable of centrifuging the extraction vessels at a rate of 4000 ± 100 rpm for 10 ± 2 min

7.0 REAGENTS AND STANDARDS

7.1 Reagent-grade chemicals, at a minimum, should be used in all tests. Unless otherwise indicated, all reagents should conform to the specifications of the Committee on Analytical Reagents of the American Chemical Society (ACS), where such specifications are available. Other grades may be used, provided the reagents are of sufficiently high purity to permit use without lessening the accuracy of the determination. Inorganic reagents and extracts should be stored in plastic to prevent interaction of constituents from glass containers. Organic reagents should be stored in glass to prevent leaching of contaminants from plastic containers.

7.2 Reagent water must be interference free. All references to water in this method refer to reagent water unless otherwise specified.

7.3 Consult Methods 9040 and 9050 for additional information regarding the preparation of reagents required for pH and specific conductance measurements.

8.0 SAMPLE COLLECTION, PRESERVATION, AND STORAGE

8.1 See Chapter Three, "Inorganic Analytes," and Chapter Four, "Organic Analytes," for sample collection and preservation information.

8.2 All solid samples should be collected using an appropriate sampling plan.

8.3 All containers should be composed of materials that minimize interaction with solution COPCs. For further information, see Chapters Three and Four.

8.4 Preservatives should not be added to samples before extraction.

8.5 Samples can be refrigerated, unless refrigeration results in an irreversible physical change to the sample.

8.6 Analytical extracts or leachates should be preserved according to the guidance given in the individual determinative methods for the COPCs.

8.7 Extract holding times should be consistent with the holding times specified in the individual determinative methods for the COPCs.

9.0 QUALITY CONTROL

9.1 Refer to Chapter One for guidance on quality assurance (QA) and quality control (QC) protocols. When inconsistencies exist between QC guidelines, method-specific QC criteria take precedence over both technique-specific criteria and Chapter One criteria, and technique-specific QC criteria take precedence over Chapter One criteria. Any effort involving the collection of analytical data should include development of a structured and systematic planning document, such as a quality assurance project plan (QAPP) or a sampling and analysis plan (SAP), which translates project objectives and specifications into directions for those who will implement the project and assess the results.

Each laboratory should maintain a formal QA program. The laboratory should also maintain records to document the quality of the data generated. Development of in-house QC limits for each method is encouraged. Use of instrument-specific QC limits is encouraged, provided such limits will generate data appropriate for use in the intended application. All data sheets and QC data should be maintained for reference or inspection.

9.2 In order to demonstrate the purity of reagents and sample contact surfaces, a method blank (e.g., a bottle without solid material but with eluent carried through the extraction, filtration and analytical sample preparation process) should be tested.

9.3 The analysis of extracts should follow appropriate QC procedures, as specified in the determinative methods for the COPCs. Refer to Chapter One for specific QC procedures.

9.4 Solid materials should be tested within one month of receipt unless the project requires that the "as-received" samples are tested sooner (e.g., the material is part of a time-dependent study or the material may change during storage due to oxidation or carbonation).

9.5 Initial demonstration of proficiency (IDP)

Leachate methods are not amenable to typical IDPs when reference materials with known values are not available. However, prior to using this method an analyst should have documented proficiency in the skills required for successful implementation of the method. For example, skill should be demonstrated in the use of an analytical balance, the determination of pH using methods 9040 and 9045 and the determination of conductance using method 9050.

10.0 CALIBRATION AND STANDARDIZATION

10.1 The balance should be calibrated and certified, at a minimum, annually or in accordance with laboratory policy.

10.2 Prior to measurement of eluate pH, the pH meter should be calibrated using a minimum of two standards that bracket the range of pH measurements. Refer to Methods 9040 and 9045 for additional guidance.

10.3 Prior to measurement of eluate conductivity, the meter should be calibrated using at least one standard at a value greater than the range of conductivity measurements. Refer to Method 9050 for additional guidance.

11.0 PROCEDURE

A flowchart of the method is presented in Figure 1. Microsoft Excel® data templates are available to aid in collecting and archiving of laboratory and analytical data.[3]

11.1 Particle size reduction (if required)

11.1.1 In this method, particle size reduction is used to prepare large-grained samples for extraction so that the approach toward liquid-solid equilibrium is enhanced and mass transport through large particles is minimized. A longer extract contact time is required for larger maximum particle size designations. This method designates three maximum particle sizes and associated contact times (see Table 2). The selection of an appropriate maximum

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[3] These Excel® templates form the basis for uploading method data into the data management program, LeachXS Lite™. Both the data templates and LeachXS Lite™ are available at http://vanderbilt.edu/leaching.

particle size from this table should be based on professional judgment regarding the practical effort required to size reduce the solid material.

11.1.2 Particle size reduction of "as received" sample may be achieved through crushing, milling, or grinding with equipment made from chemically inert materials. During the reduction process, care should be taken to minimize loss of sample and potentially volatile constituents in the sample.

11.1.3 If the moisture content of the "as-received" material is greater than 15% (wet basis), air drying or desiccation may be necessary. Oven drying is not recommended for preparation of test samples due to the potential for mineral alteration. In all cases, the moisture content of the "as received" material should be recorded.

NOTE: If the solid material is susceptible to interaction with the atmosphere (e.g., carbonation, oxidation), drying should be conducted in an inert environment.

11.1.4 When the material seems to be of a relatively uniform particle size, calculate the percentage less than the sieve size as follows:

$$\%\ \text{Passing} = \frac{M_{sieved}}{M_{total}} \times 100\%$$

Where: M_{sieved} = mass of sample passing the sieve (g)
M_{total} = mass of total sample (g) (e.g., M_{sieved} + mass not passing sieve)

11.1.5 The fraction retained by the sieve should be recycled for further particle size reduction until at least 85% of the initial mass has been reduced below the designated maximum particle size. Calculate and record the final percentage passing the sieve and the designated maximum particle size. For the uncrushable fraction of the "as received" material, record the fraction mass and nature (e.g., rock, metal or glass shards, etc).

11.1.6 Store the size-reduced material in an airtight container in order to prevent contamination via gas exchange with the atmosphere. Store the container in a cool, dark and dry place prior to use.

11.2 Determination of solids and moisture content

11.2.1 In order to provide the dry mass equivalent of the "as-tested" material, the solids content of the subject material should be determined. Often, the moisture content of the solid sample is recorded. In this method, the moisture content is determined and recorded on the basis of the "wet" or "as-tested" sample.

WARNING: The drying oven should be contained in a hood or otherwise properly ventilated. Significant laboratory contamination or inhalation hazards may result when drying heavily contaminated samples. Consult the laboratory safety officer for proper handling procedures prior to drying samples that may contain volatile, hazardous, flammable or explosive materials.

11.2.2 Place a 5 to 10-g sample of solid material into a tared dish or crucible. Dry the sample to a constant mass at 105 ± 2 °C. Check for constant mass by returning the dish to the drying oven for 24 hours, cooling to room temperature in a desiccator and re-weighing. The two mass readings should agree within the larger of 0.2% or 0.02 g.

NOTE: The oven-dried sample is not used for the extraction and should be properly disposed of once the dry mass is determined.

11.2.3 Calculate and report the solids content as follows:

$$SC = \frac{M_{dry}}{M_{test}}$$

Where: SC = solids content of "as-tested" material (g-dry/g)
M_{dry} = mass of dry material specified in the method (g-dry)
M_{test} = mass of "as-tested" solid equivalent to the dry-material mass (g)

11.2.4 Calculate and report the moisture content (wet basis) as follows:

$$MC_{wet} = \frac{M_{test} - M_{dry}}{M_{test}}$$

Where: $MC_{(wet)}$ = moisture content on a wet basis (g_{H_2O}/g)
M_{dry} = mass of dry material specified in the method (g-dry)
M_{test} = mass of "as-tested" solid equivalent to the dry-material mass (g)

11.3 Extraction setup schedule (Microsoft Excel® spreadsheet template available at http://www.vanderbilt.edu/leaching/downloads/test-methods/).

An Excel® template accompanies this method and may be used to set up the extraction schedule. If using the provided template, disregard Sec. 11.3 and proceed to the extraction procedure Sec. 11.4.

11.3.1 Using the schedule shown in Table 1 as a guide, set up five test extractions and one method blank. The mass of solids in an extraction may be scaled to minimize headspace in each extraction vessel. However, the volume of eluent should always be based on the target L/S in Column B of Table 1.

11.3.2 Calculate and record the amount of "as-tested" material equivalent to the dry mass in Column D of Table 1 as follows:

$$M_{test} = \frac{M_{dry}}{SC}$$

Where: M_{test} = mass of "as-tested" solid equivalent to the dry-material mass (g)
M_{dry} = mass of dry material specified in the method (g-dry)
SC = solids content of "as-tested" material (g-dry/g)

11.3.3 Calculate and record the volume of moisture contained in the "as-tested" sample in Column E of Table 1 as follows:

$$V_{W,sample} = \frac{M_{test} \times (1 - SC)}{\rho_w}$$

Where: $V_{W,sample}$ = volume of water in the “as tested” sample (mL)
M_{test} = mass of "as-tested" solid equivalent to the dry-material mass (g)
SC = solids content of the "as tested" sample (g-dry/g)
ρ_w = density of water (1.0 g/mL at room temperature)

11.3.4 Calculate and record the volume of reagent water required to bring each extraction to the target L/S in Column F of Table 1 as follows:

$$V_{RW} = M_{dry} \times LS - V_{W,sample}$$

Where: V_{RW} = volume of reagent water required to complete L/S (mL)
M_{dry} = mass of dry material specified in the method (g-dry)
LS = liquid-to-dry-solid ratio (10 mL/g)
$V_{W,sample}$ = volume of water in "as tested" sample (mL)

The size of the extraction bottle should be sufficient to contain the combined volume of solid material and eluent, ideally with a minimum amount of headspace.

11.4 Extraction procedure

11.4.1 Label five bottles with test position numbers and an additional bottle as a method blank according to Column A in Table 1.

11.4.2 Place the dry-mass equivalent (± 0.1 g) of "as-tested" sample as shown in Column D in Table 1 into each of the five test position extraction vessels.

NOTE: Do not put solid material in the method blank extraction vessel.

11.4.3 Add the appropriate volume (± 0.5 mL) of reagent water to both the test position and method blank extraction vessels as specified in Column F of Table 1.

11.4.4 Tighten the leak-proof lid on each bottle and tumble all extractions (i.e., test positions and method blanks) in an end-over-end fashion at a speed of 28 ± 2 rpm at room temperature (20 ± 2 °C). The contact time for this method will vary depending on the maximum particle size as shown in Table 2.

NOTE: The length of the contact time is designed to enhance the approach toward liquid-solid equilibrium. Longer contact times are required for larger particles to compensate for the effects of intra-particle diffusion. See Table 2 for required contact times based on the maximum particle size.

11.4.5 Remove the extraction vessels from the rotary tumbler and clarify the extracts by allowing the bottles to stand for 15 ± 5 min. Alternately, centrifuge the extraction vessels at 4000 ± 100 rpm for 10 ± 2 min.

NOTE: If clarification is significantly incomplete after settling or centrifugation, eluate measurements for pH, conductivity, and oxidization-reduction potential (ORP) may be taken on filtered samples. In this case, perform the filtration in Sec. 11.4.8 prior to eluate measurement in Sec. 11.4.6 and note the deviation from the written procedure.

CAUTION: Following separation from the solid phase, eluate samples lack the buffering provided by the solid phase and therefore may be susceptible to pH change resulting from interaction with air.

11.4.6 For each extraction vessel, decant a minimum volume (approximately 5 mL) of clear, unpreserved supernatant into a clean container.

11.4.7 Measure and record the pH, specific conductivity, and ORP of the extracts (see Methods 9040, 9045, and 9050).

NOTE: Measurement of pH, conductivity, and ORP should be taken within 15 minutes of eluate processing (Sec. 11.4.8) to avoid neutralization of the solution due to exposure to carbon dioxide, especially when alkaline materials are tested.

NOTE: The measurement of ORP is optional, but strongly recommended, especially when testing materials where oxidation is likely to change the LSP of COPCs.

11.4.8 Separate the solid from the remaining liquid in each extraction vessel by pressure or vacuum filtration through a clean 0.45-µm pore size membrane (Sec. 6.5). The filtration apparatus may be exchanged for a clean apparatus as often as necessary until all liquid has been filtered.

11.4.9 Immediately, preserve and store the volume(s) of eluate required for chemical analysis. Preserve all analytical samples in a manner that is consistent with the determinative chemical analyses to be performed.

12.0 DATA ANALYSIS AND CALCULATIONS (EXCEL® TEMPLATE PROVIDED)

12.1 Data reporting

12.1.1 Figure 2 shows an example of a data sheet that may be used to report the concentration results of this method. This example is included in the Excel® template. At a minimum, the basic test report should include:

a) Name of the laboratory
b) Laboratory technical contact information
c) Date and time at the start of the test
d) Name or code of the solid material
e) Particle size (85 wt% less than designated particle size)
f) Ambient temperature during extraction (°C)
g) Extraction contact time (h)
h) Eluate-specific information (see Sec. 12.1.2 below)

12.1.2 The minimum set of data that should be reported for each eluate includes:

a) Eluate sample ID
b) Target L/S (mL/g-dry)
c) Mass of "as tested" solid material used (g)
d) Moisture content of material used (g_{H_2O}/g)
e) Volume of eluent used (mL)
f) Measured final eluate pH
g) Measured eluate conductivity (mS/cm)
h) Measured ORP (mV) (optional)
i) Concentrations of all COPCs
j) Analytical QC qualifiers as appropriate

12.2 Data interpretation and presentation (optional)

12.2.1 LSP curve

12.2.1.1 A constituent LSP curve can be generated for each COPC after chemical analysis of all extracts by plotting the constituent concentration in the liquid phase as a function of L/S used for each extraction. The curve indicates the equilibrium concentration of the COPC as a function of L/S at the natural pH.

12.2.1.2 The lower limit of quantitation (LLOQ) for the analytical technique for each COPC may be shown as a horizontal line. COPC concentrations below this line indicate negligible or non-quantitative concentrations.

NOTE: The LLOQ is highly matrix-dependent and should be determined as part of a QA/QC plan.

12.2.1.3 Figure 3 provides example LSP curves as a function of L/S for a coal combustion fly ash and a coal combustion flue gas desulfurization filter cake.

13.0 METHOD PERFORMANCE

13.1 Performance data and related information are provided in SW-846 methods only as examples and guidance. The data do not represent required performance criteria for users of the methods. Instead, performance criteria should be developed on a project-specific basis, and the laboratory should establish in-house QC performance criteria for the application of this method. Performance data must not be used as absolute QC acceptance criteria for purposes of laboratory QC or accreditation.

13.2 Interlaboratory validation of this method was conducted using a coal combustion fly ash (material code EaFA), a contaminated smelter site soil (material code CFS) and a solidified waste analog (material code SWA). The median values and inner quartile ranges (IQRs) for repeatability and reproducibility were determined for eluate concentration results across all study materials and pH target values (see Table 3). More details on the interlaboratory validation may be found in Ref. 2.

13.3 Ref. 1 and Ref. 4 may provide additional guidance and insight on the use, performance and application of this method.

14.0 POLLUTION PREVENTION

14.1 Pollution prevention encompasses any technique that reduces or eliminates the quantity and/or toxicity of waste at the point of generation. Numerous opportunities for pollution prevention exist in laboratory operations. The EPA has established a preferred hierarchy of environmental management techniques that places pollution prevention as the management option of first choice. Whenever feasible, laboratory personnel should use pollution prevention techniques to address their waste generation. When wastes cannot be feasibly reduced at the source, the Agency recommends recycling as the next best option.

14.2 For information about pollution prevention that may be applicable to laboratories and research institutions consult *Less is Better: Laboratory Chemical Management for Waste Reduction,* a free publication available from the ACS, Committee on Chemical Safety, http://portal.acs.org/portal/fileFetch/C/WPCP_012290/pdf/WPCP_012290.pdf.

15.0 WASTE MANAGEMENT

The EPA requires that laboratory waste management practices be conducted consistent with all applicable rules and regulations. Laboratories are urged to protect the air, water, and land by minimizing and controlling all releases from hoods and bench operations, complying with the letter and spirit of any sewer discharge permits and regulations, and by complying with all solid and hazardous waste regulations, particularly the hazardous waste identification rules and land disposal restrictions. For further information on waste management, consult *The Waste Management Manual for Laboratory Personnel* available from ACS at the web address listed in Sec. 14.2.

16.0 REFERENCES

1. A.C. Garrabrants, D.S. Kosson, H.A. van der Sloot, F. Sanchez, and O. Hjelmar, "Background Information for the Leaching Environmental Assessment Framework (LEAF) Test Methods," EPA/600/R-10-170, *U.S. Environmental Protection Agency*, Washington, DC, 2010.

2. A.C. Garrabrants, D.S. Kosson, L. Stefanski, R. DeLapp, P.F.A.B. Seignette, H.A. van der Sloot, P. Kariher, and M. Baldwin, "Interlaboratory Validation of the Leaching Environmental Assessment (LEAF) Method 1313 and Method 1316," EPA 600/R-12/623, *Environmental Protection Agency*, Washington DC, 2012.

3. D.S. Kosson, F. Sanchez, P. Kariher, L.H. Turner, R. DeLapp, and P. Seignette, "Characterization of Coal Combustion Residues from Electric Utilities – Leaching and Characterization Data," EPA-600/R-09/151, *U.S. Environmental Protection Agency*, Washington DC, 2009.

4. D.S. Kosson, H.A. van der Sloot, F. Sanchez, and A.C. Garrabrants, "An Integrated Framework for Evaluating Leaching in Waste Management and Utilization of Secondary Materials," *Environmental Engineering Science*, 19(3) 159-204, 2002.

5. EN12457, "Characterization of Waste – Leaching – Compliance Test for Leaching of Granular Waste Materials and Sludges," *Comité Européen de Normalisation*, Brussels, Belgium, 2001.

6. F. Sanchez, R. Keeney, D.S. Kosson, and R. DeLapp, "Characterization of Mercury-Enriched Coal Combustion Residues from Electric Utilities Using Enhanced Sorbents for Mercury Control," EPA-600/R-06/008, *U.S. Environmental Protection Agency*, Washington DC, 2006.

7. F. Sanchez, D.S. Kosson, R. Keeney, R. DeLapp, L. Turner, and P. Kariher, "Characterization of Coal Combustion Residues from Electric Utilities Using Wet Scrubbers for Multi-Pollutant Control," EPA-600/R-08/077, *U.S. Environmental Protection Agency*, Washington DC, 2008.

17.0 TABLES, DIAGRAMS, FLOWCHARTS, AND VALIDATION DATA

The following pages contain the tables and figures referenced by this method.

TABLE 1

EXAMPLE SCHEDULE FOR EXTRACTION SETUP

A	B	C	D	E	F	G
Test Position	Target LS	Minimum Dry Mass (g-dry)	Mass of "As-Tested" Sample (g)	Moisture in "As-Tested" Sample (mL)	Volume of Reagent Water (mL)	Recommended Bottle Size (mL)
T01	10.0	20	22.2	2.2	198	250
T02	5.0	40	44.4	4.4	196	250
T03	2.0	100	111.1	11.1	189	500
T04	1.0	200	222.2	22.2	178	500
T05	0.5	400	444.4	44.4	156	1000
B03	QC	–	–	–	200	250
Total	–	–	844.4	–	1120	–

NOTE: 1) This schedule assumes a target liquid volume of 200 mL.
2) This schedule is based on "as tested" solids content of 0.90 g-dry/g.
3) Test position marked B01 is a method blank of reagent water.

Table data modified from Ref. 4.

TABLE 2

EXTRACTION PARAMETERS AS FUNCTION OF MAXIMUM PARTICLE SIZE

Particle Size (85% less than) (mm)	US Sieve Size	Minimum Dry Mass (g-dry)	Contact Time (h)	Recommended Vessel size (mL)
0.3	50	20 ± 0.05	24 ± 2	250
2.0	10	40 ± 0.1	48 ± 2	500
5.0	4	80 ± 0.1	72 ± 2	1000

TABLE 3

MEDIAN METHOD PRECISION ACROSS STUDY MATERIALS

Analyte	Symbol	Repeatability - Median %RSD_r	Repeatability - IQR %RSD_r	Reproducibility - Median %RSD_R	Reproducibility - IQR % RSD_R
Antimony	Sb	12%	8-13%	21%	17-27%
Arsenic	As	15%	12-28%	31%	23-34%
Barium	Ba	7%	5-9%	16%	13-30%
Boron	B	7%	5-10%	13%	9-34%
Calcium	Ca	6%	3-7%	8%	7-19%
Molybdenum	Mo	7%	6-9%	18%	11-31%
Selenium	Se	8%	4-9%	20%	13-24%
Vanadium	V	6%	4-12%	16%	13-26%
Median of Medians	–	7%	3-28%	17%	7-34%

Data taken from Ref. 2.

FIGURE 1

METHOD FLOWCHART

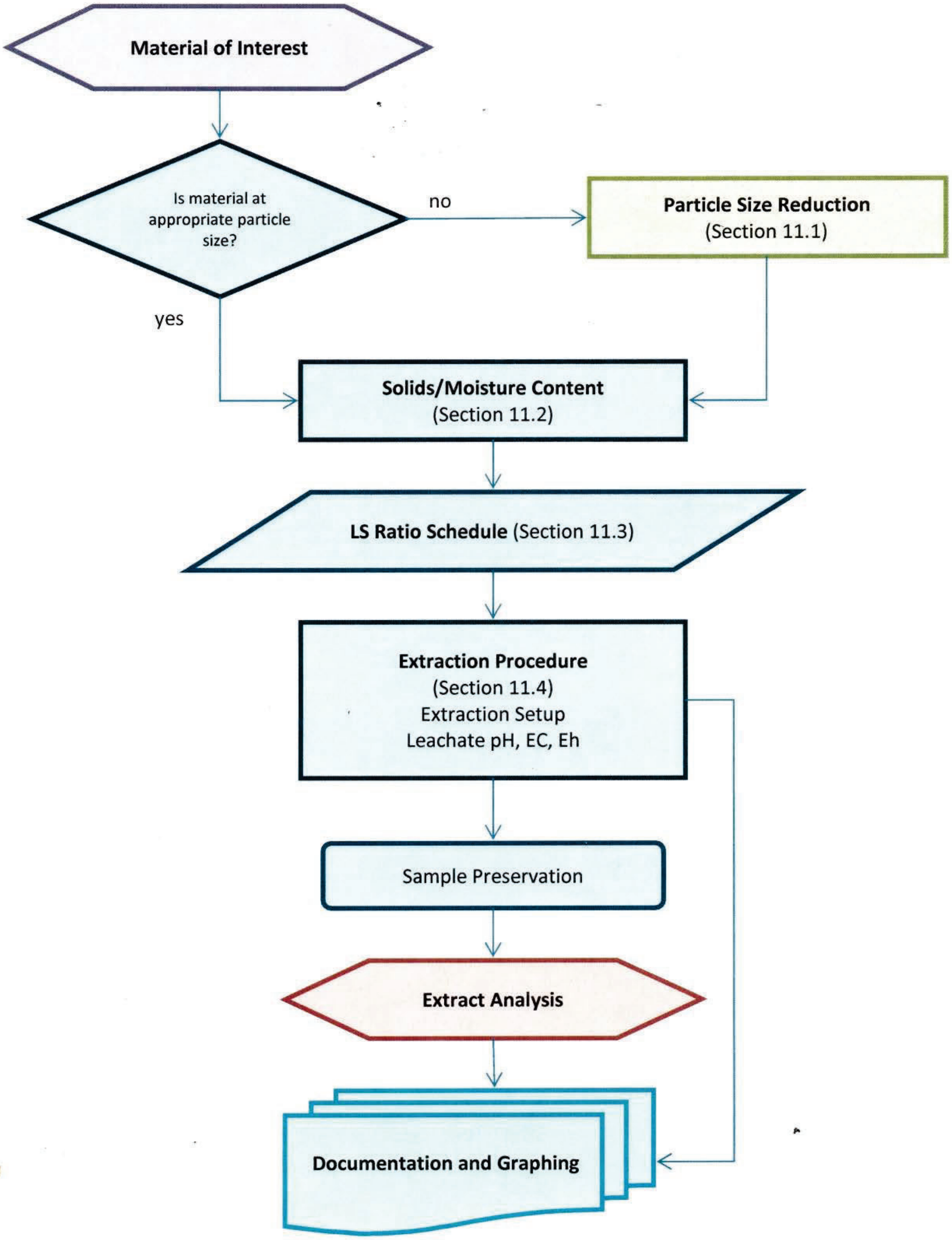


FIGURE 2

EXAMPLE DATA REPORTING FORMAT

EPA METHOD 1316
Report of Analysis

ABC Laboratories
123 Main Street
Anytown, USA
Contact: John Smith
(555) 111-1111

Client Contact: Susan Jones
(555) 222-2222

Material Code:	**FAX**	Particle Size:	88% passing 2-mm sieve
Material Type:	Coal Combustion Fly Ash	Contact Time:	860 g
Date Received:	10/1/20xx	Lab Temperature:	21 ± 2 °C
Test Start Date:	11/1/20xx	Eluent Used:	ASTM Type II Water
Report Date:	12/1/20xx		

Test Position	Replicate	Value	Units	Method	Note
T01	**A**				
	Eluate Sample ID	**XYZ-1316-T01-A**			
	Solid Material	40.0	g		
	Moisture Content	0.01	g_{H_2O}/g		
	Water Added	386.0	mL		
	Target L/S	10.0	mL/g-dry		
	Eluate pH	1.89	–	EPA 9040	
	Eluate Conductivity	12.6	mS/cm	EPA 9050	
	Eluate ORP	203	mv		

Chemical Analysis	Value	Units	QC Flag	Method	Date	Dilution Factor
Al	216.0	mg/L		EPA 6020	11/7/20xx	1000
As	7.64	mg/L		EPA 6020	11/7/20xx	10
Cl	< 4.13	mg/L	U	EPA 9056	11/9/20xx	1

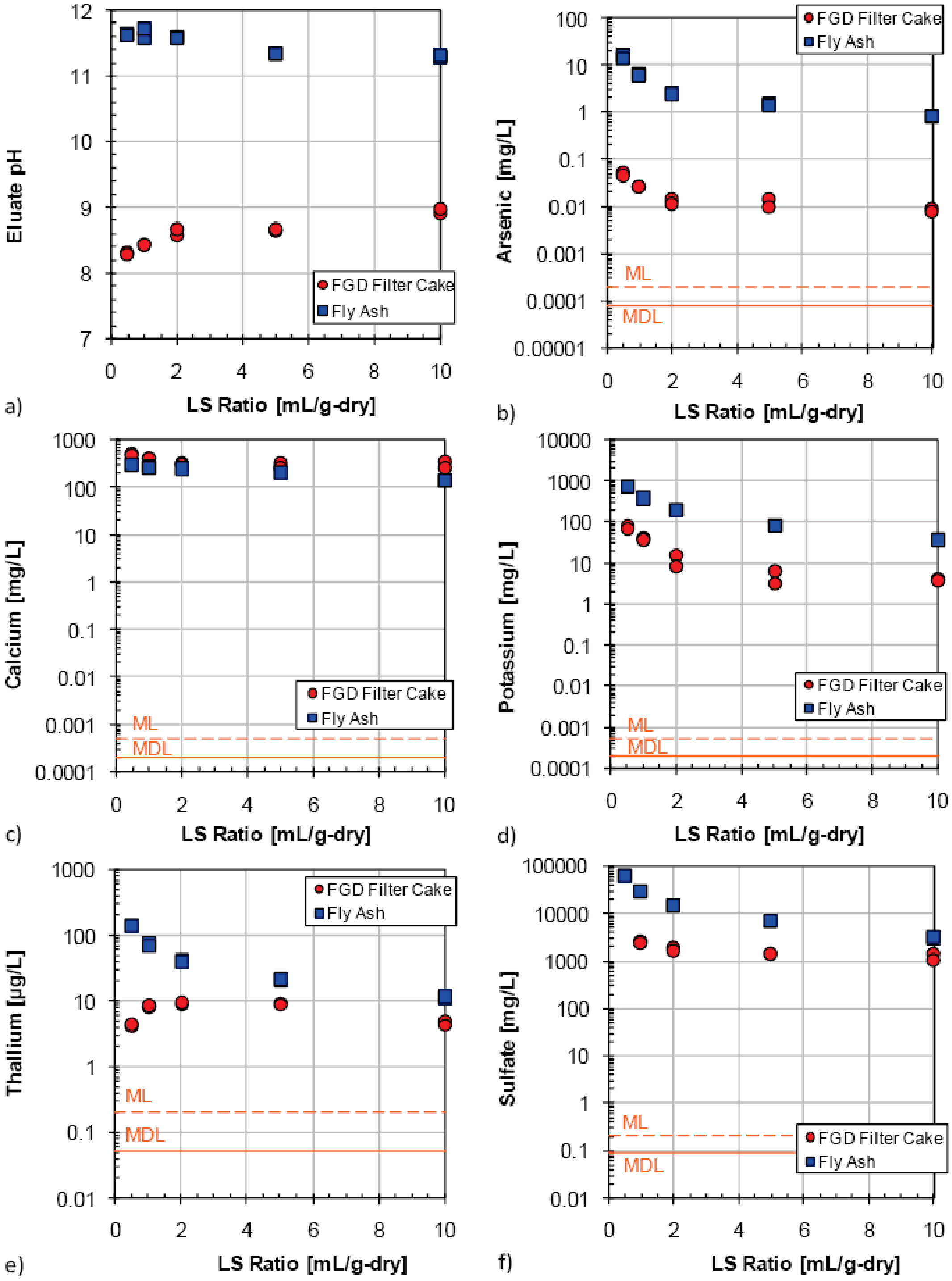
Test Position	Replicate	Value	Units	Method	Note
T02	**A**				
	Eluate Sample ID	**XYZ-1316-T02-A**			
	Solid Material	20.0	g		
	Moisture Content	0.01	g_{H_2O}/g		
	Water Added	400.0	mL		
	Target L/S	5.0	mL/g-		
	Eluate pH	3.86	–	EPA 9040	
	Eluate Conductivity	0.99	mS/cm	EPA 9050	
	Eluate ORP	180	mv		

Chemical Analysis	Value	Units	QC Flag	Method	Date	Dilution Factor
Al	449.0	mg/L		EPA 6020	11/7/20xx	1000
As	97.9	mg/L		EPA 6020	11/7/20xx	10
Cl	< 4.13	mg/L	U	EPA 9056	11/7/20xx	1

QC Flag Key: U Value below lower limit of quantitation as reported (<"LLOQ")

FIGURE 3

EXAMPLE CONCENTRATON RESULTS FROM A COAL COMBUSTION FLY ASH AND FLUE-GAS DESULFURIZATION FILTER CAKE



DOCUMENT

7

U.S. ENVIRONMENTAL PROTECTION AGENCY REGION I

LOW STRESS (low flow) PURGING AND SAMPLING PROCEDURE FOR THE COLLECTION OF GROUNDWATER SAMPLES FROM MONITORING WELLS

Quality Assurance Unit
U.S. Environmental Protection Agency – Region 1
11 Technology Drive
North Chelmsford, MA 01863

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Prepared by:__________________________________ ____________
(Robert Reinhart, Quality Assurance Unit) Date

Approved by:__________________________________ ____________
(John Smaldone, Quality Assurance Unit) Date

Revision Page

Date	**Rev #**	**Summary of changes**	**Sections**
7/30/96	1	Finalized	
01/19/10	2	Updated	All sections
3/23/17	3	Updated	All sections
9/20/17	4	Updated	Section 7.0

Table of Contents

1.0 USE OF TERMS

Equipment blank: The equipment blank shall include the pump and the pump's tubing. If tubing is dedicated to the well, the equipment blank needs only to include the pump in subsequent sampling rounds. If the pump and tubing are dedicated to the well, the equipment blank is collected prior to its placement in the well. If the pump and tubing will be used to sample multiple wells, the equipment blank is normally collected after sampling from contaminated wells and not after background wells.

Field duplicates: Field duplicates are collected to determine precision of the sampling procedure. For this procedure, collect duplicate for each analyte group in consecutive order (VOC original, VOC duplicate, SVOC original, SVOC duplicate, etc.).

Indicator field parameters: This SOP uses field measurements of turbidity, dissolved oxygen, specific conductance, temperature, pH, and oxidation/reduction potential (ORP) as indicators of when purging operations are sufficient and sample collection may begin.

Matrix Spike/Matrix Spike Duplicates: Used by the laboratory in its quality assurance program. Consult the laboratory for the sample volume to be collected.

Potentiometric Surface: The level to which water rises in a tightly cased well constructed in a confined aquifer. In an unconfined aquifer, the potentiometric surface is the water table.

QAPP: Quality Assurance Project Plan

SAP: Sampling and Analysis Plan

SOP: Standard operating procedure

Stabilization: A condition that is achieved when all indicator field parameter measurements are sufficiently stable (as described in the “Monitoring Indicator Field Parameters” section) to allow sample collection to begin.

Temperature blank: A temperature blank is added to each sample cooler. The blank is measured upon receipt at the laboratory to assess whether the samples were properly cooled during transit.

Trip blank (VOCs): Trip blank is a sample of analyte-free water taken to the sampling site and returned to the laboratory. The trip blanks (one pair) are added to each sample cooler that contains VOC samples.

2.0 SCOPE & APPLICATION

The goal of this groundwater sampling procedure is to collect water samples that reflect the total mobile organic and inorganic loads (dissolved and colloidal sized fractions) transported through the subsurface under ambient flow conditions, with minimal physical and chemical alterations from sampling operations. This standard operating procedure (SOP) for collecting groundwater samples will help ensure that the project's data quality objectives (DQOs) are met under certain low-flow conditions.

The SOP emphasizes the need to minimize hydraulic stress at the well-aquifer interface by maintaining low water-level drawdowns, and by using low pumping rates during purging and sampling operations. Indicator field parameters (e.g., dissolved oxygen, pH, etc.) are monitored during purging in order to determine when sample collection may begin. Samples properly collected using this SOP are suitable for analysis of groundwater contaminants (volatile and semi-volatile organic analytes, dissolved gases, pesticides, PCBs, metals and other inorganics), or naturally occurring analytes. This SOP is based on Puls, and Barcelona (1996).

This procedure is designed for monitoring wells with an inside diameter (1.5-inches or greater) that can accommodate a positive lift pump with a screen length or open interval ten feet or less and with a water level above the top of the screen or open interval (Hereafter, the "screen or open interval" will be referred to only as "screen interval"). This SOP is not applicable to other well-sampling conditions.

While the use of dedicated sampling equipment is not mandatory, dedicated pumps and tubing can reduce sampling costs significantly by streamlining sampling activities and thereby reducing the overall field costs.

The goal of this procedure is to emphasize the need for consistency in deploying and operating equipment while purging and sampling monitoring wells during each sampling event. This will help to minimize sampling variability.

This procedure describes a general framework for groundwater sampling. Other site specific information (hydrogeological context, conceptual site model (CSM), DQOs, etc.) coupled with systematic planning must be added to the procedure in order to develop an appropriate site specific SAP/QAPP. In addition, the site specific SAP/QAPP must identify the specific equipment that will be used to collect the groundwater samples.

This procedure does not address the collection of water or free product samples from wells containing free phase LNAPLs and/or DNAPLs (light or dense non-aqueous phase liquids). For this type of situation, the reader may wish to check: Cohen, and Mercer (1993) or other pertinent documents.

This SOP is to be used when collecting groundwater samples from monitoring wells at all Superfund, Federal Facility and RCRA sites in Region 1 under the conditions described herein. Request for modification of this SOP, in order to better address specific situations at individual wells, must include adequate technical justification for proposed changes. All changes and modifications must be approved and included in a revised SAP/QAPP before implementation in field.

3.0 BACKGROUND FOR IMPLEMENTATION

It is expected that the monitoring well screen has been properly located (both laterally and vertically) to intercept existing contaminant plume(s) or along flow paths of potential contaminant migration. Problems with inappropriate monitoring well placement or faulty/improper well installation cannot be overcome by even the best water sampling procedures. This SOP presumes that the analytes of interest are moving (or will potentially move) primarily through the more permeable zones intercepted by the screen interval.

Proper well construction, development, and operation and maintenance cannot be overemphasized. The use of installation techniques that are appropriate to the hydrogeologic setting of the site often prevent "problem well" situations from occurring. During well development, or redevelopment, tests should be conducted to determine the hydraulic characteristics of the monitoring well. The data can then be used to set the purging/sampling rate, and provide a baseline for evaluating changes in well performance and the potential need for well rehabilitation. Note: if this installation data or well history (construction and sampling) is not available or discoverable, for all wells to be sampled, efforts to build a sampling history should commence with the next sampling event.

The pump intake should be located within the screen interval and at a depth that will remain under water at all times. It is recommended that the intake depth and pumping rate remain the same for all sampling events. The mid-point or the lowest historical midpoint of the saturated screen length is often used as the location of the pump intake. For new wells, or for wells without pump intake depth information, the site’s SAP/QAPP must provide clear reasons and instructions on how the pump intake depth(s) will be selected, and reason(s) for the depth(s) selected. If the depths to top and bottom of the well screen are not known, the SAP/QAPP will need to describe how the sampling depth will be determined and how the data can be used.

Stabilization of indicator field parameters is used to indicate that conditions are suitable for sampling to begin. Achievement of turbidity levels of less than 5 NTU, and stable drawdowns of less than 0.3 feet, while desirable, are not mandatory. Sample collection may still take place provided the indicator field parameter criteria in this procedure are met. If after 2 hours of purging indicator field parameters have not stabilized, one of three optional courses of action may be taken: a) continue purging until stabilization is achieved, b) discontinue purging, do not collect any samples, and record in log book that stabilization could not be achieved (documentation must describe attempts to achieve stabilization), c) discontinue purging, collect samples and provide full explanation of attempts to achieve stabilization (note: there is a risk that the analytical data obtained, especially metals and strongly hydrophobic organic analytes, may reflect a sampling bias and therefore, the data may not meet the data quality objectives of the sampling event).

It is recommended that low-flow sampling be conducted when the air temperature is above 32°F (0°C). If the procedure is used below 32°F, special precautions will need to be taken to prevent the groundwater from freezing in the equipment. Because sampling during freezing temperatures may adversely impact the data quality objectives, the need for water sample collection during months when these conditions are likely to occur should be evaluated during site planning and special sampling measures may need to be developed. Ice formation in the flow-through-cell will cause the monitoring probes to act erratically. A transparent flow-through-cell needs to be used to observe if ice is forming in the cell. If ice starts to form on the other pieces of the sampling equipment, additional problems may occur.

4.0 HEALTH & SAFETY

When working on-site, comply with all applicable OSHA requirements and the site's health/safety procedures. All proper personal protection clothing and equipment are to be worn. Some samples may contain biological and chemical hazards. These samples should be handled with suitable protection to skin, eyes, etc.

5.0 CAUTIONS

The following cautions need to be considered when planning to collect groundwater samples when the below conditions occur.

If the groundwater degasses during purging of the monitoring well, dissolved gases and VOCs will be lost. When this happens, the groundwater data for dissolved gases (e.g., methane, ethene, ethane, dissolved oxygen, etc.) and VOCs will need to be qualified. Some conditions that can promote degassing are the use of a vacuum pump (e.g., peristaltic pumps), changes in aperture along the sampling tubing, and squeezing/pinching the pump's tubing which results in a pressure change.

When collecting the samples for dissolved gases and VOCs analyses, avoid aerating the groundwater in the pump's tubing. This can cause loss of the dissolved gases and VOCs in the groundwater. Having the pump's tubing completely filled prior to sampling will avoid this problem when using a centrifugal pump or peristaltic pump.

Direct sun light and hot ambient air temperatures may cause the groundwater in the tubing and flow-through-cell to heat up. This may cause the groundwater to degas which will result in loss of VOCs and dissolved gases. When sampling under these conditions, the sampler will need to shade the equipment from the sunlight (e.g., umbrella, tent, etc.). If possible, sampling on hot days, or during the hottest time of the day, should be avoided. The tubing exiting the monitoring well should be kept as short as possible to avoid the sun light or ambient air from heating up the groundwater.

Thermal currents in the monitoring well may cause vertical mixing of water in the well bore. When the air temperature is colder than the groundwater temperature, it can cool the top of the water column. Colder water which is denser than warm water sinks to the bottom of the well and the warmer water at the bottom of the well rises, setting up a convection cell. "During low-flow sampling, the pumped water may be a mixture of convecting water from within the well casing and aquifer water moving inward through the screen. This mixing of water during low-flow sampling can substantially increase equilibration times, can cause false stabilization of indicator parameters, can give false indication of redox state, and can provide biological data that are not representative of the aquifer conditions" (Vroblesky 2007).

Failure to calibrate or perform proper maintenance on the sampling equipment and measurement instruments (e.g., dissolved oxygen meter, etc.) can result in faulty data being collected.

Interferences may result from using contaminated equipment, cleaning materials, sample containers, or uncontrolled ambient/surrounding air conditions (e.g., truck/vehicle exhaust nearby).

Cross contamination problems can be eliminated or minimized through the use of dedicated sampling equipment and/or proper planning to avoid ambient air interferences. Note that the use of dedicated sampling equipment can also significantly reduce the time needed to complete each sampling event, will promote consistency in the sampling, and may reduce sampling bias by having the pump's intake at a constant depth.

Clean and decontaminate all sampling equipment prior to use. All sampling equipment needs to be routinely checked to be free from contaminants and equipment blanks collected to ensure that the equipment is free of contaminants. Check the previous equipment blank data for the site (if they exist) to determine if the previous cleaning procedure removed the contaminants. If contaminants were detected and they are a concern, then a more vigorous cleaning procedure will be needed.

6.0 PERSONNEL QUALIFICATIONS

All field samplers working at sites containing hazardous waste must meet the requirements of the OSHA regulations. OSHA regulations may require the sampler to take the 40 hour OSHA health and safety training course and a refresher course prior to engaging in any field activities, depending upon the site and field conditions.

The field samplers must be trained prior to the use of the sampling equipment, field instruments, and procedures. Training is to be conducted by an experienced sampler before initiating any sampling procedure.

The entire sampling team needs to read, and be familiar with, the site Health and Safety Plan, all relevant SOPs, and SAP/QAPP (and the most recent amendments) before going onsite for the sampling event. It is recommended that the field sampling leader attest to the understanding of these site documents and that it is recorded.

7.0 EQUIPMENT AND SUPPLIES

A. Informational materials for sampling event

A copy of the current Health and Safety Plan, SAP/QAPP, monitoring well construction data, location map(s), field data from last sampling event, manuals for sampling, and the monitoring instruments' operation, maintenance, and calibration manuals should be brought to the site.

B. Well keys.

C. Extraction device

Adjustable rate, submersible pumps (e.g., centrifugal, bladder, etc.) which are constructed of stainless steel or polytetrafluoroethylene (PTFE, i.e. Teflon®) are preferred. PTFE, however, should not be used when sampling for per- and polyfluoroalkyl substances (PFAS) as it is likely to contain these substances.

Note: If extraction devices constructed of other materials are to be used, adequate information must be provided to show that the substituted materials do not leach contaminants nor cause interferences to the analytical procedures to be used. Acceptance of these materials must be obtained before the sampling event.

If bladder pumps are selected for the collection of VOCs and dissolved gases, the pump setting should be set so that one pulse will deliver a water volume that is sufficient to fill a 40 mL VOC vial. This is not mandatory, but is considered a "best practice". For the proper operation, the bladder pump will need a minimum amount of water above the pump; consult the manufacturer for the recommended submergence. The pump's recommended submergence value should be determined during the planning stage, since it may influence well construction and placement of dedicated pumps where water-level fluctuations are significant.

Adjustable rate, peristaltic pumps (suction) are to be used with caution when collecting samples for VOCs and dissolved gases (e.g., methane, carbon dioxide, etc.) analyses. Additional information on the use of peristaltic pumps can be found in Appendix A.
If peristaltic pumps are used, the inside diameter of the rotor head tubing needs to match the inside diameter of the tubing installed in the monitoring well.

Inertial pumping devices (motor driven or manual) are not recommended. These devices frequently cause greater disturbance during purging and sampling, and are less easily controlled than submersible pumps (potentially increasing turbidity and sampling variability, etc.). This can lead to sampling results that are adversely affected by purging and sampling operations, and a higher degree of data variability.

D. Tubing

PTFE (Teflon®) or PTFE-lined polyethylene tubing are preferred when sampling is to include VOCs, SVOCs, pesticides, PCBs and inorganics. As discussed in the previous section, PTFE tubing should not be used when sampling for PFAS. In this case, a suitable alternative such as high-density polyethylene tubing should be used.

PVC, polypropylene or polyethylene tubing may be used when collecting samples for metal and other inorganics analyses.

Note: If tubing constructed of other materials is to be used, adequate information must be provided to show that the substituted materials do not leach contaminants nor cause interferences to the analytical procedures to be used. Acceptance of these materials must be obtained before the sampling event.

The use of 1/4 inch or 3/8 inch (inside diameter) tubing is recommended. This will help ensure that the tubing remains liquid filled when operating at very low pumping rates when using centrifugal and peristaltic pumps.

Silastic tubing should be used for the section around the rotor head of a peristaltic pump. It should be less than a foot in length. The inside diameter of the tubing used at the pump rotor head must be the same as the inside diameter of tubing placed in the well. A tubing connector is used to connect the pump rotor head tubing to the well tubing. Alternatively, the two pieces of tubing can be connected to each other by placing the one end of the tubing inside the end of the other tubing. The tubing must not be reused.

E. The water level measuring device

Electronic ”tape”, pressure transducer, water level sounder/level indicator, etc. should be capable of measuring to 0.01 foot accuracy. Recording pressure transducers, mounted above the pump, are especially helpful in tracking water levels during pumping operations, but their use must include check measurements with a water level “tape” at the start and end of each sampling event.

F. Flow measurement supplies

Graduated cylinder (size according to flow rate) and stopwatch usually will suffice.

Large graduated bucket used to record total water purged from the well.

G. Interface probe

To be used to check on the presence of free phase liquids (LNAPL, or DNAPL) before purging begins (as needed).

H. Power source (generator, nitrogen tank, battery, etc.)

When a gasoline generator is used, locate it downwind and at least 30 feet from the well so that the exhaust fumes do not contaminate samples.

I. Indicator field parameter monitoring instruments

Use of a multi-parameter instrument capable of measuring pH, oxidation/reduction potential (ORP), dissolved oxygen (DO), specific conductance, temperature, and coupled with a flow-through-cell is required when measuring all indicator field parameters, except turbidity. Turbidity is collected using a separate instrument. Record equipment/instrument identification (manufacturer, and model number).

Transparent, small volume flow-through-cells (e.g., 250 mLs or less) are preferred. This allows observation of air bubbles and sediment buildup in the cell, which can interfere with the operation of the monitoring instrument probes, to be easily detected. A small volume cell facilitates rapid turnover of water in the cell between measurements of the indicator field parameters.

It is recommended to use a flow-through-cell and monitoring probes from the same manufacturer and model to avoid incompatibility between the probes and flow-through-cell.

Turbidity samples are collected before the flow-through-cell. A “T” connector coupled with a valve is connected between the pump’s tubing and flow-through-cell. When a turbidity measurement is required, the valve is opened to allow the groundwater to flow into a container. The valve is closed and the container sample is then placed in the turbidimeter.

Standards are necessary to perform field calibration of instruments. A minimum of two standards are needed to bracket the instrument measurement range for all parameters except ORP which use a Zobell solution as a standard. For dissolved oxygen, a wet sponge used for the 100% saturation and a zero dissolved oxygen solution are used for the calibration.

Barometer (used in the calibration of the Dissolved Oxygen probe) and the conversion formula to convert the barometric pressure into the units of measure used by the Dissolved Oxygen meter are needed.

J. Decontamination supplies

Includes (for example) non-phosphate detergent, distilled/deionized water, isopropyl alcohol, etc.

K. Record keeping supplies

Logbook(s), well purging forms, chain-of-custody forms, field instrument calibration forms, etc.

L. Sample bottles

M. Sample preservation supplies (as required by the analytical methods)

N. Sample tags or labels

O. PID or FID instrument

If appropriate, to detect VOCs for health and safety purposes, and provide qualitative field evaluations.

P. Miscellaneous Equipment

Equipment to keep the sampling apparatus shaded in the summer (e.g., umbrella) and from freezing in the winter. If the pump's tubing is allowed to heat up in the warm weather, the cold groundwater may degas as it is warmed in the tubing.

8.0 EQUIPMENT/INSTRUMENT CALIBRATION

Prior to the sampling event, perform maintenance checks on the equipment and instruments according to the manufacturer's manual and/or applicable SOP. This will ensure that the equipment/instruments are working properly before they are used in the field.

Prior to sampling, the monitoring instruments must be calibrated and the calibration documented. The instruments are calibrated using U.S Environmental Protection Agency Region 1 *Calibration of Field Instruments (temperature, pH, dissolved oxygen, conductivity/specific conductance, oxidation/reduction [ORP], and turbidity)*, March 23, 2017, or latest version or from one of the methods listed in 40CFR136, 40CFR141 and SW-846.

The instruments shall be calibrated at the beginning of each day. If the field measurement falls outside the calibration range, the instrument must be re-calibrated so that all measurements fall within the calibration range. At the end of each day, a calibration check is performed to verify that instruments remained in calibration throughout the day. This check is performed while the instrument is in measurement mode, not calibration mode. If the field instruments are being used to monitor the natural attenuation parameters, then a calibration check at mid-day is highly recommended to ensure that the instruments did not drift out of calibration. Note: during the day if the instrument reads zero or a negative number for dissolved oxygen, pH, specific conductance, or turbidity (negative value only), this indicates that the instrument drifted out of calibration or the instrument is malfunctioning. If this situation occurs the data from this instrument will need to be qualified or rejected.

9.0 PRELIMINARY SITE ACTIVITIES (as applicable)

Check the well for security (damage, evidence of tampering, missing lock, etc.) and record pertinent observations (include photograph as warranted).

If needed, lay out a sheet of clean polyethylene for monitoring and sampling equipment, unless equipment is elevated above the ground (e.g., on a table, etc.).

Remove well cap and if appropriate measure VOCs at the rim of the well with a PID or FID instrument and record reading in field logbook or on the well purge form.

If the well casing does not have an established reference point (usually a V-cut or indelible mark in the well casing), make one. Describe its location and record the date of the mark in the logbook (consider a photographic record as well). All water level measurements must be recorded relative to this reference point (and the altitude of this point should be determined using techniques that are appropriate to site's DQOs.

If water-table or potentiometric surface map(s) are to be constructed for the sampling event, perform synoptic water level measurement round (in the shortest possible time) before any purging and sampling activities begin. If possible, measure water level depth (to 0.01 ft.) and total well depth (to 0.1 ft.) the day before sampling begins, in order to allow for re-settlement of any particulates in the water column. This is especially important for those wells that have not been recently sampled because sediment buildup in the well may require the well to be redeveloped. If measurement of total well depth is not made the day before, it should be measured after sampling of the well is complete. All measurements must be taken from the established referenced point. Care should be taken to minimize water column disturbance.

Check newly constructed wells for the presence of LNAPLs or DNAPLs before the initial sampling round. If none are encountered, subsequent check measurements with an interface probe may not be necessary unless analytical data or field analysis signal a worsening situation. This SOP cannot be used in the presence of LNAPLs or DNAPLs. If NAPLs are present, the project team must decide upon an alternate sampling method. All project modifications must be approved and documented prior to implementation.

If available check intake depth and drawdown information from previous sampling event(s) for each well. Duplicate, to the extent practicable, the intake depth and extraction rate (use final pump dial setting information) from previous event(s). If changes are made in the intake depth or extraction rate(s) used during previous sampling event(s), for either portable or dedicated extraction devices, record new values, and explain reasons for the changes in the field logbook.

10.0 PURGING AND SAMPLING PROCEDURE

Purging and sampling wells in order of increasing chemical concentrations (known or anticipated) are preferred.

The use of dedicated pumps is recommended to minimize artificial mobilization and entrainment of particulates each time the well is sampled. Note that the use of dedicated sampling equipment can also significantly reduce the time needed to complete each sampling event, will promote consistency in the sampling, and may reduce sampling bias by having the pump's intake at a constant depth.

A. Initial Water Level

Measure the water level in the well before installing the pump if a non-dedicated pump is being used. The initial water level is recorded on the purge form or in the field logbook.

B. Install Pump

Lower pump, safety cable, tubing and electrical lines slowly (to minimize disturbance) into the well to the appropriate depth (may not be the mid-point of the screen/open interval). The Sampling and Analysis Plan/Quality Assurance Project Plan should specify the sampling depth (used previously), or provide criteria for selection of intake depth for each new well. If possible keep the pump intake at least two feet above the bottom of the well, to minimize mobilization of particulates present in the bottom of the well.

Pump tubing lengths, above the top of well casing should be kept as short as possible to minimize heating the groundwater in the tubing by exposure to sun light and ambient air temperatures. Heating may cause the groundwater to degas, which is unacceptable for the collection of samples for VOC and dissolved gases analyses.

C. Measure Water Level

Before starting pump, measure water level. Install recording pressure transducer, if used to track drawdowns, to initialize starting condition.

D. Purge Well

From the time the pump starts purging and until the time the samples are collected, the purged water is discharged into a graduated bucket to determine the total volume of groundwater purged. This information is recorded on the purge form or in the field logbook.

Start the pump at low speed and slowly increase the speed until discharge occurs. Check water level. Check equipment for water leaks and if present fix or replace the affected equipment. Try to match pumping rate used during previous sampling event(s). Otherwise, adjust pump speed until there is little or no water level drawdown. If the minimal drawdown that can be achieved exceeds 0.3 feet, but remains stable, continue purging.

Monitor and record the water level and pumping rate every five minutes (or as appropriate) during purging. Record any pumping rate adjustments (both time and flow rate). Pumping rates should, as needed, be reduced to the minimum capabilities of the pump to ensure stabilization of the water level. Adjustments are best made in the first fifteen minutes of pumping in order to help minimize purging time. During pump start-up, drawdown may exceed the 0.3 feet target and then "recover" somewhat as pump flow adjustments are made. Purge volume calculations should utilize stabilized drawdown value, not the initial drawdown. If the initial water level is above the top of the screen do not allow the water level to fall into the well screen. The final purge volume must be greater than the stabilized drawdown volume plus the pump’s tubing volume. If the drawdown has exceeded 0.3 feet and stabilizes, calculate the volume of water between the initial water level and the stabilized water level. Add the volume of the water which occupies the pump’s tubing to this calculation. This combined volume of water needs to be purged from the well after the water level has stabilized before samples are collected.

Avoid the use of constriction devices on the tubing to decrease the flow rate because the constrictor will cause a pressure difference in the water column. This will cause the groundwater to degas and result in a loss of VOCs and dissolved gasses in the groundwater samples.

Note: the flow rate used to achieve a stable pumping level should remain constant while monitoring the indicator parameters for stabilization and while collecting the samples.

Wells with low recharge rates may require the use of special pumps capable of attaining very low pumping rates (e.g., bladder, peristaltic), and/or the use of dedicated equipment. For new monitoring wells, or wells where the following situation has not occurred before, if the recovery rate to the well is less than 50 mL/min., or the well is being essentially dewatered during purging, the well should be sampled as soon as the water level has recovered sufficiently to collect the volume needed for all anticipated samples. The project manager or field team leader will need to make the decision when samples should be collected, how the sample is to be collected, and the reasons recorded on the purge form or in the field logbook. A water level measurement needs to be performed and recorded before samples are collected. If the project manager decides to collect the samples using the pump, it is best during this recovery period that the pump intake tubing not be removed, since this will aggravate any turbidity problems. Samples in this specific situation may be collected without stabilization of indicator field parameters. Note that field conditions and efforts to overcome problematic situations must be recorded in order to support field decisions to deviate from normal procedures described in this SOP. If this type of problematic situation persists in a well, then water sample collection should be changed to a passive or no-purge method, if consistent with the site's DQOs, or have a new well installed.

E. Monitor Indicator Field Parameters

After the water level has stabilized, connect the "T" connector with a valve and the flow-through-cell to monitor the indicator field parameters. If excessive turbidity is anticipated or encountered with the pump startup, the well may be purged for a while without connecting up the flow-through-cell, in order to minimize particulate buildup in the cell (This is a judgment call made by the sampler). Water level drawdown measurements should be made as usual. If possible, the pump may be installed the day before purging to allow particulates that were disturbed during pump insertion to settle.

During well purging, monitor indicator field parameters (turbidity, temperature, specific conductance, pH, ORP, DO) at a frequency of five minute intervals or greater. The pump's flow rate must be able to "turn over" at least one flow-through-cell volume between measurements (for a 250 mL flow-through-cell with a flow rate of 50 mLs/min., the monitoring frequency would be every five minutes; for a 500 mL flow-through-cell it would be every ten minutes). If the cell volume cannot be replaced in the five minute interval, then the time between measurements must be increased accordingly. <u>Note: during the early phase of purging, emphasis should be put on minimizing and stabilizing pumping stress, and recording those adjustments followed by stabilization of indicator parameters. Purging is considered complete and sampling may begin when all the above indicator field parameters have stabilized. Stabilization is considered to be achieved when three consecutive readings are within the following limits:</u>

Turbidity (10% for values greater than 5 NTU; if three Turbidity values are less than 5 NTU, consider the values as stabilized),
Dissolved Oxygen (10% for values greater than 0.5 mg/L, if three Dissolved Oxygen values are less than 0.5 mg/L, consider the values as stabilized),
Specific Conductance (3%),
Temperature (3%),
pH (± 0.1 unit),
Oxidation/Reduction Potential (±10 millivolts).

All measurements, except turbidity, must be obtained using a flow-through-cell. Samples for turbidity measurements are obtained before water enters the flow-through-cell. Transparent flow-through-cells are preferred, because they allow field personnel to watch for particulate build-up within the cell. This build-up may affect indicator field parameter values measured within the cell. If the cell needs to be cleaned during purging operations, continue pumping and disconnect cell for cleaning, then reconnect after cleaning and continue monitoring activities. Record start and stop times and give a brief description of cleaning activities.

The flow-through-cell must be designed in a way that prevents gas bubble entrapment in the cell. Placing the flow-through-cell at a 45 degree angle with the port facing upward can help remove bubbles from the flow-through-cell (see Appendix B Low-Flow Setup Diagram). Throughout the measurement process, the flow-through-cell must remain free of any gas bubbles. Otherwise, the monitoring probes may act erratically. When the pump is turned off or cycling on/off (when using a bladder pump), water in the cell must not drain out. Monitoring probes must remain submerged in water at all times.

F. Collect Water Samples

When samples are collected for laboratory analyses, the pump’s tubing is disconnected from the “T” connector with a valve and the flow-through-cell. The samples are collected directly from the pump’s tubing. Samples must not be collected from the flow-through-cell or from the “T” connector with a valve.

VOC samples are normally collected first and directly into pre-preserved sample containers. However, this may not be the case for all sampling locations; the SAP/QAPP should list the order in which the samples are to be collected based on the project’s objective(s). Fill all sample containers by allowing the pump discharge to flow gently down the inside of the container with minimal turbulence.

If the pump’s flow rate is too high to collect the VOC/dissolved gases samples, collect the other samples first. Lower the pump’s flow rate to a reasonable rate and collect the VOC/dissolved gases samples and record the new flow rate.

During purging and sampling, the centrifugal/peristaltic pump tubing must remain filled with water to avoid aeration of the groundwater. It is recommended that 1/4 inch or 3/8 inch (inside diameter) tubing be used to help ensure that the sample tubing remains water filled. If the pump tubing is not completely filled to the sampling point, use the following procedure to collect samples: collect non-VOC/dissolved gases samples first, then increase flow rate slightly until the water completely fills the tubing, collect the VOC/dissolved gases samples, and record new drawdown depth and flow rate.

For bladder pumps that will be used to collect VOC or dissolved gas samples, it is recommended that the pump be set to deliver long pulses of water so that one pulse will fill a 40 mL VOC vial.

Use pre-preserved sample containers or add preservative, as required by analytical methods, to the samples immediately after they are collected. Check the analytical methods (e.g. EPA SW-846, 40 CFR 136, water supply, etc.) for additional information on preservation.

If determination of filtered metal concentrations is a sampling objective, collect filtered water samples using the same low flow procedures. The use of an in-line filter (transparent housing preferred) is required, and the filter size (0.45 µm is commonly used) should be based on the sampling objective. Pre-rinse the filter with groundwater prior to sample collection. Make sure the filter is free of air bubbles before samples are collected. Preserve the filtered water sample immediately. Note: filtered water samples are not an acceptable substitute for unfiltered samples when the monitoring objective is to obtain chemical concentrations of total mobile contaminants in groundwater for human health or ecological risk calculations.

Label each sample as collected. Samples requiring cooling will be placed into a cooler with ice or refrigerant for delivery to the laboratory. Metal samples after acidification to a pH less than 2 do not need to be cooled.

G. Post Sampling Activities

If a recording pressure transducer is used to track drawdown, re-measure water level with tape.

After collection of samples, the pump tubing may be dedicated to the well for re-sampling (by hanging the tubing inside the well), decontaminated, or properly discarded.

Before securing the well, measure and record the well depth (to 0.1 ft.), if not measured the day before purging began. Note: measurement of total well depth annually is usually sufficient after the initial low stress sampling event. However, a greater frequency may be needed if the well has a “silting” problem or if confirmation of well identity is needed.

Secure the well.

11.0 DECONTAMINATION

Decontaminate sampling equipment prior to use in the first well, and then following sampling of each subsequent well. Pumps should not be removed between purging and sampling operations. The pump, tubing, support cable and electrical wires which were in contact with the well should be decontaminated by one of the procedures listed below.

The use of dedicated pumps and tubing will reduce the amount of time spent on decontamination of the equipment. If dedicated pumps and tubing are used, only the initial sampling event will require decontamination of the pump and tubing.

Note if the previous equipment blank data showed that contaminant(s) were present after using the below procedure or the one described in the SAP/QAPP, a more vigorous procedure may be needed.

<u>Procedure 1</u>

Decontaminating solutions can be pumped from either buckets or short PVC casing sections through the pump and tubing. The pump may be disassembled and flushed with the decontaminating solutions. It is recommended that detergent and alcohol be used sparingly in the decontamination process and water flushing steps be extended to ensure that any sediment trapped in the pump is removed. The pump exterior and electrical wires must be rinsed with the decontaminating solutions, as well. The procedure is as follows:

Flush the equipment/pump with potable water.

Flush with non-phosphate detergent solution. If the solution is recycled, the solution must be changed periodically.

Flush with potable or distilled/deionized water to remove all of the detergent solution. If the water is recycled, the water must be changed periodically.

Optional - flush with isopropyl alcohol (pesticide grade; must be free of ketones {e.g., acetone}) or with methanol. This step may be required if the well is highly contaminated or if the equipment blank data from the previous sampling event show that the level of contaminants is significant.

Flush with distilled/deionized water. This step must remove all traces of alcohol (if used) from the equipment. The final water rinse must not be recycled.

<u>Procedure 2</u>

Steam clean the outside of the submersible pump.

Pump hot potable water from the steam cleaner through the inside of the pump. This can be accomplished by placing the pump inside a three or four inch diameter PVC pipe with end cap. Hot water from the steam cleaner jet will be directed inside the PVC pipe and the pump exterior will be cleaned. The hot water from the steam cleaner will then be pumped from the PVC pipe through the pump and collected into another container. Note: additives or solutions should not be added to the steam cleaner.

Pump non-phosphate detergent solution through the inside of the pump. If the solution is recycled, the solution must be changed periodically.

Pump potable water through the inside of the pump to remove all of the detergent solution. If the solution is recycled, the solution must be changed periodically.

Pump distilled/deionized water through the pump. The final water rinse must not be recycled.

12.0 FIELD QUALITY CONTROL

Quality control samples are required to verify that the sample collection and handling process has not compromised the quality of the groundwater samples. All field quality control samples must be prepared the same as regular investigation samples with regard to sample volume, containers, and preservation. Quality control samples include field duplicates, equipment blanks, matrix spike/matrix spike duplicates, trip blanks (VOCs), and temperature blanks.

13.0 FIELD LOGBOOK

A field log shall be kept to document all groundwater field monitoring activities (see Appendix C, example table), and record the following for each well:

Site name, municipality, state.

Well identifier, latitude-longitude or state grid coordinates.

Measuring point description (e.g., north side of PVC pipe).

Well depth, and measurement technique.

Well screen length.

Pump depth.

Static water level depth, date, time and measurement technique.

Presence and thickness of immiscible liquid (NAPL) layers and detection method.

Pumping rate, drawdown, indicator parameters values, calculated or measured total volume pumped, and clock time of each set of measurements.

Type of tubing used and its length.

Type of pump used.

Clock time of start and end of purging and sampling activity.

Types of sample bottles used and sample identification numbers.

Preservatives used.

Parameters requested for analyses.

Field observations during sampling event.

Name of sample collector(s).

Weather conditions, including approximate ambient air temperature.

QA/QC data for field instruments.

Any problems encountered should be highlighted.

Description of all sampling/monitoring equipment used, including trade names, model number, instrument identification number, diameters, material composition, etc.

14.0 DATA REPORT

Data reports are to include laboratory analytical results, QA/QC information, field indicator parameters measured during purging, field instrument calibration information, and whatever other field logbook information is needed to allow for a full evaluation of data usability.

Note: the use of trade, product, or firm names in this sampling procedure is for descriptive purposes only and does not constitute endorsement by the U.S. EPA.

15.0 REFERENCES

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APPENDIX A

PERISTALTIC PUMPS

Before selecting a peristaltic pump to collect groundwater samples for VOCs and/or dissolved gases, (e.g., methane, carbon dioxide, etc.) consideration should be given to the following:

- The decision of whether or not to use a peristaltic pump is dependent on the intended use of the data.
- If the additional sampling error that may be introduced by this device is NOT of concern for the VOC/dissolved gases data's intended use, then this device may be acceptable.
- If minor differences in the groundwater concentrations could affect the decision, such as to continue or terminate groundwater cleanup or whether the cleanup goals have been reached, then this device should NOT be used for VOC/dissolved gases sampling. In these cases, centrifugal or bladder pumps are a better choice for more accurate results.

EPA and USGS have documented their concerns with the use of the peristaltic pumps to collect water sample in the below documents.

- "Suction Pumps are not recommended because they may cause degassing, pH modification, and loss of volatile compounds" *A Compendium of Superfund Field Operations Methods*, EPA/540/P-87/001, December 1987.
- "The agency does not recommend the use of peristaltic pumps to sample ground water particularly for volatile organic analytes" *RCRA Ground-Water Monitoring Draft Technical Guidance*, EPA Office of Solid Waste, November 1992.
- "The peristaltic pump is limited to shallow applications and can cause degassing resulting in alteration of pH, alkalinity, and volatiles loss", *Low-flow (Minimal drawdown) Ground-Water Sampling Procedures*, by Robert Puls & Michael Barcelona, April 1996, EPA/540/S-95/504.
- "Suction-lift pumps, such as peristaltic pumps, can operate at a very low pumping rate; however, using negative pressure to lift the sample can result in the loss of volatile analytes", USGS Book 9 Techniques of Water-Resources Investigation, Chapter A4. (Version 2.0, 9/2006).

APPENDIX B

SUMMARY OF SAMPLING INSTRUCTIONS

These instructions are for using an adjustable rate, submersible pump or a peristaltic pump with the pump’s intake placed at the midpoint of a 10 foot or less well screen or an open interval. The water level in the monitoring well is above the top of the well screen or open interval, the ambient temperature is above 32°F, and the equipment is not dedicated. Field instruments are already calibrated. The equipment is setup according to the diagram at the end of these instructions.

1. Review well installation information. Record well depth, length of screen or open interval, and depth to top of the well screen. Determine the pump’s intake depth (e.g., mid-point of screen/open interval).

2. On the day of sampling, check security of the well casing, perform any safety checks needed for the site, lay out a sheet of polyethylene around the well (if necessary), and setup the equipment. If necessary a canopy or an equivalent item can be setup to shade the pump’s tubing and flow-through-cell from the sun light to prevent the sun light from heating the groundwater.

3. Check well casing for a reference mark. If missing, make a reference mark. Measure the water level (initial) to 0.01 ft. and record this information.

4. Install the pump’s intake to the appropriate depth (e.g., midpoint) of the well screen or open interval. Do not turn-on the pump at this time.

5. Measure water level and record this information.

6. Turn-on the pump and discharge the groundwater into a graduated waste bucket. Slowly increase the flow rate until the water level starts to drop. Reduce the flow rate slightly so the water level stabilizes. Record the pump’s settings. Calculate the flow rate using a graduated container and a stop watch. Record the flow rate. Do not let the water level drop below the top of the well screen.

If the groundwater is highly turbid or discolored, continue to discharge the water into the bucket until the water clears (visual observation); this usually takes a few minutes. The turbid or discolored water is usually from the well-being disturbed during the pump installation. If the water does not clear, then you need to make a choice whether to continue purging the well (hoping that it will clear after a reasonable time) or continue to the next step. Note, it is sometimes helpful to install the pump the day before the sampling event so that the disturbed materials in the well can settle out.

If the water level drops to the top of the well screen during the purging of the well, stop purging the well, and do the following:

> Wait for the well to recharge to a sufficient volume so samples can be collected. This may take a while (pump may be removed from well, if turbidity is not a problem). The project manager will need to make the decision when samples should be collected and the reasons recorded in the site's log book. A water level measurement needs to be performed and recorded before samples are collected. When samples are being collected, the water level must not drop below the top of the screen or open interval. Collect the samples from the pump's tubing. Always collect the VOCs and dissolved gases samples first. Normally, the samples requiring a small volume are collected before the large volume samples are collected just in case there is not sufficient water in the well to fill all the sample containers. All samples must be collected, preserved, and stored according to the analytical method. Remove the pump from the well and decontaminate the sampling equipment.

If the water level has dropped 0.3 feet or less from the initial water level (water level measure before the pump was installed); proceed to Step 7. If the water level has dropped more than 0.3 feet, calculate the volume of water between the initial water level and the stabilized water level. Add the volume of the water which occupies the pump's tubing to this calculation. This combined volume of water needs to be purged from the well after the water level has stabilized before samples are be collected.

7. Attach the pump's tubing to the "T" connector with a valve (or a three-way stop cock). The pump's tubing from the well casing to the "T" connector must be as short as possible to prevent the groundwater in the tubing from heating up from the sun light or from the ambient air. Attach a short piece of tubing to the other end of the end of the "T" connector to serve as a sampling port for the turbidity samples. Attach the remaining end of the "T" connector to a short piece of tubing and connect the tubing to the flow-through-cell bottom port. To the top port, attach a small piece of tubing to direct the water into a calibrated waste bucket. Fill the cell with the groundwater and remove all gas bubbles from the cell. Position the flow-through-cell in such a way that if gas bubbles enter the cell they can easily exit the cell. If the ports are on the same side of the cell and the cell is cylindrical shape, the cell can be placed at a 45-degree angle with the ports facing upwards; this position should keep any gas bubbles entering the cell away from the monitoring probes and allow the gas bubbles to exit the cell easily (see Low-Flow Setup Diagram). Note:

make sure there are no gas bubbles caught in the probes' protective guard; you may need to shake the cell to remove these bubbles.

8. Turn-on the monitoring probes and turbidity meter.

9. Record the temperature, pH, dissolved oxygen, specific conductance, and oxidation/reduction potential measurements. Open the valve on the "T" connector to collect a sample for the turbidity measurement, close the valve, do the measurement, and record this measurement. Calculate the pump's flow rate from the water exiting the flow-through-cell using a graduated container and a stop watch, and record the measurement. Measure and record the water level. Check flow-through-cell for gas bubbles and sediment; if present, remove them.

10. Repeat Step 9 every 5 minutes or as appropriate until monitoring parameters stabilized. Note: at least one flow-through-cell volume must be exchanged between readings. If not, the time interval between readings will need to be increased. Stabilization is achieved when three consecutive measurements are within the following limits:

> **Turbidity** (10% for values greater than 5 NTUs; if three Turbidity values are less than 5 NTUs, consider the values as stabilized),
> **Dissolved Oxygen** (10% for values greater than 0.5 mg/L, if three Dissolved Oxygen values are less than 0.5 mg/L, consider the values as stabilized),
> **Specific Conductance** (3%),
> **Temperature** (3%),
> **pH** (± 0.1 unit),
> **Oxidation/Reduction Potential** (±10 millivolts).

If these stabilization requirements do not stabilize in a reasonable time, the probes may have been coated from the materials in the groundwater, from a buildup of sediment in the flow-through-cell, or a gas bubble is lodged in the probe. The cell and the probes will need to be cleaned. Turn-off the probes (not the pump), disconnect the cell from the "T" connector and continue to purge the well. Disassemble the cell, remove the sediment, and clean the probes according to the manufacturer's instructions. Reassemble the cell and connect the cell to the "T" connector. Remove all gas bubbles from the cell, turn-on the probes, and continue the measurements. Record the time the cell was cleaned.

11. When it is time to collect the groundwater samples, turn-off the monitoring probes, and disconnect the pump's tubing from the "T" connector. If you are using a centrifugal or peristaltic pump check the pump's tubing to determine if the tubing is completely filled with water (no air space).

All samples must be collected and preserved according to the analytical method. VOCs and dissolved gases samples are normally collected first and directly into pre-preserved sample containers. However, this may not be the case for all sampling locations; the SAP/QAPP should list the order in which the samples are to be collected based on the project's objective(s). Fill all sample containers by allowing the pump discharge to flow gently down the inside of the container with minimal turbulence.

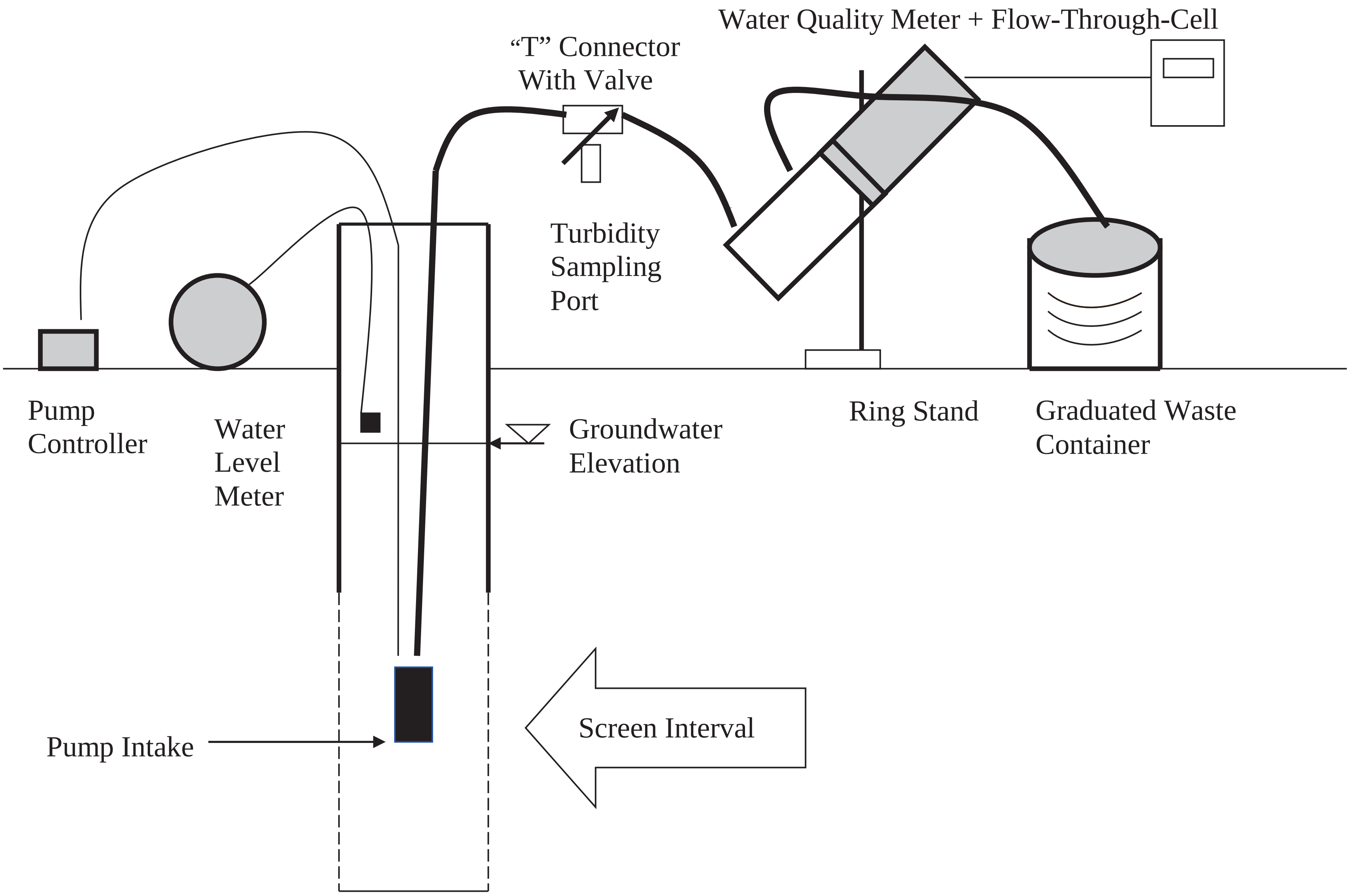
If the pump's tubing is not completely filled with water and the samples are being collected for VOCs and/or dissolved gases analyses using a centrifugal or peristaltic pump, do the following:

> All samples must be collected and preserved according to the analytical method. The VOCs and the dissolved gases (e.g., methane, ethane, ethene, and carbon dioxide) samples are collected last. When it becomes time to collect these samples increase the pump's flow rate until the tubing is completely filled. Collect the samples and record the new flow rate.

12. Store the samples according to the analytical method.

13. Record the total purged volume (graduated waste bucket). Remove the pump from the well and decontaminate the sampling equipment.

Low-Flow Setup Diagram



APPENDIX C

EXAMPLE (Minimum Requirements)

WELL PURGING-FIELD WATER QUALITY MEASUREMENTS FORM

Location (Site/Facility Name)________________________________
Well Number_________________ Date________________________
Field Personnel____
Sampling Organization_______________________________________
Identify MP____

Depth to ________/_________ of screen
(below MP) top bottom
Pump Intake at (ft. below MP)_________
Purging Device; (pump type)__________
Total Volume Purged ________________

Clock Time 24 HR	Water Depth below MP ft	Pump Dial[1]	Purge Rate ml/min	Cum. Volume Purged liters	Temp. "C	Spec. Cond.[2] µS/cm	pH	ORP[3] mv	DO mg/L	Tur-bidity NTU	Comments

Stabilization Criteria 3% 3% ±0.1 ±10 mv 10% 10%

1. Pump dial setting (for example: hertz, cycles/min, etc).
2. µSiemens per cm(same as µmhos/cm)at 25°C.
3. Oxidation reduction potential (ORP)

DOCUMENT
8

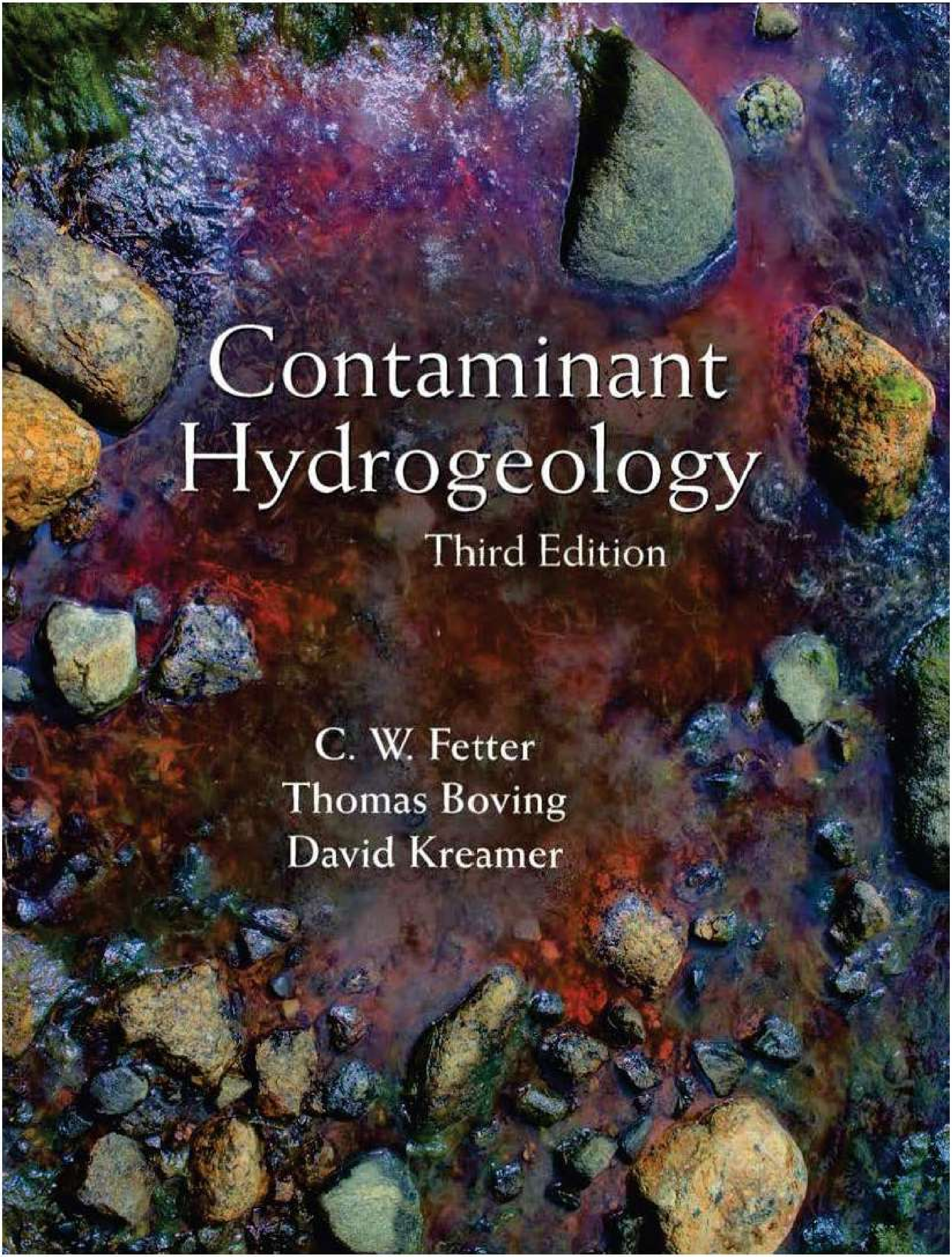


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TABLE 1.3 *Cont'd*

Contaminant	Examples of uses
Other hydrocarbons	
Alkyl sulfonates	Detergents
Cyclohexane	Organic synthesis, solvent, oil extraction
l,3,5,7-Cyclooctatetraene	Organic research
Dicyclopentadiene (DCPD)	Intermediate for insecticides, paints and varnishes, flame retardants
2,3-Dimethylhexane	NA
Fuel oil	Fuel, heating
Gasoline	Fuel
Jet fuels	Fuel
Kerosene	Fuel, heating solvent, insecticides
Lignin	Newsprint, ceramic binder, dyestuffs, drilling fuel additive, plastics
Methylene blue activated substances (MBAS)	Dyestuffs, analytical chemistry
Propane	Fuel, solvent, refrigerants, propellants, organic synthesis
Tannin	Chemical manufacturing, tanning, textiles, electroplating, inks, pharmaceuticals, photography, paper
4,6,8-Trimethyl-1-nonene	NA
Undecane	Petroleum research, organic synthesis
Metals and cations	
Aluminum	Alloys, foundry, paints, protective coatings, electrical industry, packaging, building and construction, machinery and equipment
Antimony	Hardening alloys, solders, sheet and pipe, pyrotechnics
Arsenic	Alloys, dyestuffs, medicine, solders, electronic devices, insecticides, rodenticides, herbicide, preservative
Barium	Alloys, lubricant
Beryllium	Structural material in space technology, inertial guidance systems, additive to rocket fuels, moderator and reflector of neutrons in nuclear reactors
Cadmium	Alloys, coatings, batteries, electrical equipment, fire-protection systems, paints, fungicides, photography
Calcium	Alloys, fertilizers, reducing agent
Chromium	Alloys, protective coatings, paints, nuclear and high-temperature research

(*Cont'd*)

TABLE 1.3 *Cont'd*

Contaminant	Examples of uses
Cobalt	Alloys, ceramics, drugs, paints, glass, printing, catalyst, electroplating, lamp filaments
Copper	Alloys, paints, electrical wiring, machinery, construction materials, electroplating, piping, insecticides
Iron	Alloys, machinery, magnets
Lead	Alloys, batteries, gasoline additive, sheet and pipe, paints, radiation shielding
Lithium	Alloys, pharmaceuticals, coolant, batteries, solders, propellants
Magnesium	Alloys, batteries, pyrotechnics, precision instruments, optical mirrors
Manganese	Alloys, purifying agent
Mercury	Alloys, electrical apparatus, instruments, fungicides, bactericides, mildew proofing, paper, pharmaceuticals
Molybdenum	Alloys, pigments, lubricant
Nickel	Alloys, ceramics, batteries, electroplating, catalyst
Palladium	Alloys, catalyst, jewelry, protective coatings, electrical equipment
Potassium	Alloys, catalyst
Selenium	Alloys, electronics, ceramics, catalyst
Silver	Alloys, photography, chemical manufacturing, mirrors, electronic equipment, jewelry, equipment, catalyst, pharmaceuticals
Sodium	Chemical manufacturing, catalyst, coolant, nonglare lighting for highways, laboratory reagent
Thallium	Alloys, glass, pesticides, photoelectric applications
Titanium	Alloys, structural materials, abrasives, coatings
Vanadium	Alloys, catalysts, target material for x-rays
Zinc	Alloys, electroplating, electronics, automotive parts, fungicides, roofing, cable wrappings, nutrition
Nonmetals and anions	
Ammonia	Fertilizers, chemical manufacturing, refrigerants, synthetic fibers, fuels, dyestuffs
Boron	Alloys, fibers and filaments, semiconductors, propellants
Chlorides	Chemical manufacturing, water purification, shrink-proofing, flame retardants, food processing

(Cont'd)

TABLE 1.3 *Cont'd*

Contaminant	Examples of uses
Cyanides	Polymer production (heavy duty tires), coatings, metallurgy, pesticides
Fluorides	Toothpastes and other dentrifices, additive to drinking water, aluminum smelting
Nitrates	Fertilizers, food preservatives
Nitrites	Fertilizers, food preservatives
Phosphates	Detergents, fertilizers, food additives
Sulfates	Fertilizers, pesticides
Sulfites	Pulp production and processing, food preservatives
Microorganisms	
Bacteria (coliform)	
Giardia	
Viruses	
Radionuclides	
Cesium 137	Gamma radiation source for certain foods
Chromium 51	Diagnosis of blood volume, blood cell life, cardiac output, etc.
Cobalt 60	Radiation therapy, irradiation, radiographic testing, research
Iodine 131	Medical diagnosis, therapy, leak detection, tracers (e.g., to study efficiency of mixing pulp fibers, chemical reactions, and thermal stability of additives to food products), measuring film thicknesses
Iron 59	Medicine, tracer
Lead 210	NA
Phosphorus 32	Tracer, medical treatment, industrial measurements (e.g., tire-tread wear and thickness of films and ink)
Plutonium 238, 243	Energy source, weaponry
Radium 226	Medical treatment, radiography
Radium 228	Naturally occurring
Radon 222	Medicine, leak detection, radiography, flow rate measurement
Ruthenium I06	Catalyst
Scandium 46	Tracer studies, leak detection, semiconductors
Strontium 90	Medicine, industrial applications (e.g., measuring thicknesses, density control)

(*Cont'd*)

TABLE 1.3 *Cont'd*

Contaminant	Examples of uses
Thorium 232	Naturally occurring
Tritium	Tracer, luminous instrument dials
Uranium 238	Nuclear reactors, mining operations
Zinc 65	Industrial tracers (e.g., to study wear in alloys, galvanizing, body metabolism, function of oil additives in lubricating oils)
Zirconium 95	NA

[a]NA: No information in Standard sources.

Source: Office of Technology Assessment 1984, with additions.

It should be noted that many compounds can have multiple names, making identification of compounds difficult for the environmental practitioner. In one example from Table 1.3, the compound butoxymethylbenzene can also be known by at least 26 other names or numerical distinctions (Chemspider 2015). Nomenclature can be further confused, as there are other names given for the same compound by different suppliers and vendors. Using the same example of butoxymethylbenzene above, a selective list of vendors in 2015 and their designations for the compound would include at least 14 different additional names or numerical distinctions (Zincdocking 2015). This multiple nomenclature for the same compound can be even more confused with the manufacture and use of mixtures of potential groundwater pollutants, some containing unspecified impurities. There are many types of industrial chemical mixtures in use or being developed, with multiple names and descriptions, including tens of thousands of pesticide products. Also, in recent years there has been increased concern over "emerging" organic contaminants, which were previously not yet industrially developed, not yet discovered in the environment often due to analytical limitations, or alternatively, not yet recognized as potential pollutants. These compounds include pharmaceuticals, personal care products, industrial chemicals, and hormones. Table 1.4 lists some of these compounds and their uses.

The occurrence of the substances found on Tables 1.3 and 1.4 can be detected only if a groundwater sample has been collected and analyzed. In low concentrations most of these substances are colorless, tasteless, and odorless. Specific analytical techniques must be employed to detect the presence and concentration of each substance. Some methods can be employed to analyze a sample for all of the compounds of a particular class. For example, certain organic compounds fall into a class called volatile organic compounds. There are analytical methods that could target all compounds of this class. Likewise, there are methods available to analyze for many of the metals in a single sample. However, other compounds require a specific test. With so many potential contaminants, it is possible that a sample could be collected and tested and a specific contaminant still not be found because no analysis was done for that compound or element.

compounds are potential groundwater contaminants that can leach from soil used for land applications of wastes and wastewater.

1.5.2 Category II: Sources Designed to Store, Treat and/or Dispose of Substances

Landfills Landfills are, by definition, designed to minimize adverse effects of waste disposal (Miller, 1980). However, many were poorly designed and are leaking liquids, generically termed **leachate**, which are contaminating groundwater. Landfills can contain nonhazardous municipal waste, nonhazardous industrial waste, or hazardous waste as defined by the Resource Conservation and Recovery Act. Peterson (1983) reported that there were 12,991 landfills in the United States in the 1980s, including 2,395 open dumps. According to the EPA, by 2009 landfills were much larger, but there were only 1,908 solid waste municipal landfills reported. This does not include landfills for construction and demolition wastes, nonhazardous industrial waste landfills, or hazardous waste landfills. There are an unknown number of abandoned landfills.

Materials placed in landfills include such things as municipal garbage and trash, demolition debris, sludge from wastewater-treatment plants, incinerator ash, foundry sand and other foundry wastes, and toxic and hazardous materials. Although no longer permitted in the United States, liquid hazardous waste was disposed in landfills in the past. The U.S. Environmental Protection Agency (2015) estimated that in 2012 over 250 million tons of municipal waste was generated, which is over a three-fold increase in the last half century. The World Bank (2012) has estimated worldwide municipal waste generation at 1.3 billion tons per year with estimates of expected increase to 2.2 billion tons annually in 2025, and over 11 billion by 2100. Total solid waste generation (beyond just municipal waste) is considerably larger at an estimated 11.2 billion tons in 2011 (United Nations Environmental Programme). Interactive waste atlases have also been developed to summarize worldwide waste data (e.g., http://www.atlas.d-waste.com/).

Leachate is formed from the liquids found in the waste as well as by leaching of the solid waste by rainwater. Table 1.9 contains information on the chemical composition of leachate from municipal landfills. To minimize the amount of leachate generated, modern landfills are built in sections, with a low-permeability cover placed over the waste as soon as possible to limit the infiltration of rainwater. Modern landfills also have low-permeability liner systems and collection pipes to remove the leachate that forms so that it can be taken to a wastewater-treatment plant. A modern landfill that is properly sited with respect to the local geology and that has a properly designed and constructed liner, leachate collection system, and low-permeability cover has limited potential to contaminate groundwater. However, many landfills do not have liners and leachate collection systems. In the past, landfills tended to be placed in any convenient hole or low spot, such as a sand pit, quarry, or marsh. Groundwater contamination from such landfills is highly probable.

Municipal landfills are usually located near urban areas. The trend is toward large landfills that can handle many thousands of tons of waste per year. Hazardous-waste landfills are now regulated under the Resource Conservation and Recovery Act. There is frequently strong local opposition to the siting of either a municipal or a hazardous waste landfill. This is referred to as the NIMBY syndrome: **N**ot **I**n **M**y **B**ack **Y**ard!

Homeowners may pour waste liquids into ditches or the sanitary sewer; combustibles may be burned in the backyard. These are undesirable practices that can easily result in environmental pollution, including groundwater contamination.

Surface impoundments Pits, ponds, and lagoons are used by industries, farmers, and municipalities for the storage and/or treatment of both liquid nonhazardous and hazardous waste and the discharge of nonhazardous waste. Prior to the passage of the Resource Conservation and Recovery Act, liquid hazardous wastes were also discharged into pits. These pits may be unlined or lined with natural material, such as clay, or artificial materials, such as plastic sheets, rubber membranes, or asphalt.

Impoundments are used to treat wastewater by such processes as settling of solids, biological oxidation, chemical coagulation and precipitation, and pH adjustment. They may also be used to store wastewater prior to treatment. Water from surface impoundments may be discharged to a receiving water course such as a stream or a lake. Unless a discharging impoundment is lined, it will also lose water by seepage into the subsurface. Nondischarging impoundments release water either by evaporation or seepage into the ground or a combination of both. Evaporation ponds are effective only in arid regions, where potential evapotranspiration far exceeds precipitation. Even evaporation ponds that were originally lined may leak and result in groundwater contamination if the liner deteriorates from contact with the pond's contents.

Impoundments are used for wastewater treatment by municipalities and industries such as paper manufacturing, petroleum refining, metals industry, mining, and chemical manufacturing. They are also used for treatment of agricultural waste, such as farm animal waste from feedlots. Power plants use surface impoundments as cooling ponds. Mining operations use surface ponds for the separation of tailings, which is waste rock from the processing of ore that occurs in a slurry mixture of liquid and solid.

Although it is now prohibited, until the 1970s lagoons were used for the disposal of untreated wastewater from manufacturing, ore processing, and other industrial uses into the groundwater. Brine pits were used for many years in the oil patch for the disposal of brines pumped up with the oil. Miller (1980) lists 57 cases of groundwater contamination caused by the leakage of wastewater from surface impoundments. In most of the reported cases water-supply wells had been affected; at the time when use of such impoundments was allowed, groundwater monitoring was not required; usually the only way that leakage was detected was by contamination of a supply well.

In one case in Illinois, up to 500,000 gals per day of mineralized wastewater, containing high total dissolved solids (TDS), which included chloride, sulfate, and calcium, from an ore-processing plant were discharged into waste-disposal ponds excavated in a glacial drift aquifer for a period of about 40 years. Concentrations of chloride, sulfate, TDS, and hardness were elevated in an underlying bedrock aquifer as much as a mile away from the site (U.S. Nuclear Regulatory Commission 1983).

Wastewater from the manufacturing of nerve gas and pesticides at the Rocky Mountain Arsenal at Denver was discharged into unlined evaporation ponds from 1942 until 1956. In 1956 a new pond lined with asphalt was constructed; ultimately that liner failed and the lined pond also leaked. Contamination of nearby farm wells was first detected in 1951 and was especially severe in the drought year of 1954, when irrigated crops died. Groundwater contamination extended at least 8 miles from the ponds and was indicated by high chloride content. Ultimately the groundwater under and near the Rocky Mountain Arsenal was found to contain dozens of synthetic organic chemicals, including two that are especially mobile in the subsurface: diisopropylmethylphosphonate (DIMP), a by-product of the manufacture of nerve gas, and dicyclopentadiene (DCPD) a chemical used in the manufacture of pesticides (Konikow and Thompson 1984; Spanggord, Chou, and Mabey 1979). By 2010, after 23 years of active remediation the cleanup of contaminated soil and groundwater at the Rocky Mountain Arsenal, the cost has been $2.1 billion dollars as parcels of the land are taken off the National Priorities list and tracts of land are converted to a National Wildlife Refuge.

There is very little information available on the number of surface impoundments worldwide, nor much up-to-date information from individual countries. Several decades ago the EPA performed a survey of the surface impoundments located in the United States (U.S. EPA 1983). They reported a total of 180,973 impoundments, including 37,185 municipal; 19,437 agricultural; 27,912 industrial; 25,038 mining; 65,688 brine pits for oil and gas; and 5,913 miscellaneous. A later U.S. EPA (2001) survey conducted in the 1990s estimated about 18,000 industrial impoundments. Energy related industrial surface impoundments are of particular concern, as these can hold many sorts of materials including coal combustion residues, water associated with *in situ* uranium leaching, and/or brines associated with deep oil and gas development. The large number of impoundments provides a significant threat to groundwater resources (OTA 1984).

Mine wastes Mining can produce spoils, or unneeded soil, sediment, and rock moved during the mining process, and tailings, or solid waste left over after the processing of ore. These wastes may be piled on the land surface, used to fill low areas, used to restore the land to pre-mining contours, or placed in engineered landfills with leachatecollection systems. Mine wastes can generate leachate as rainwater passes through them. If sulfate or sulfide minerals are present, sulfuric acid can be generated, and the resulting drainage water can be acidic. This is likely to occur with coal-mining wastes, copper and gold ores, and ores from massive sulfide mineralization. Mine-waste leachate may also contain heavy metals and, in the case of uranium and thorium mines, radionuclides. Neutralization of the mine wastes can prevent the formation of acidic leachate and prevent the mobilization of many, but not all, metallic ions and radionuclides. The mine-waste disposal issue is a large one. In the United States, mining is estimated to produce waste material annually with a weight of nearly nine times that of refuse generated by all cities and towns (U.S. EPA 2003). The mining of many metals traditionally requires huge quantities of rock to be removed, for example, the production of a single ton of copper ore typically generates well over 100 times the tonnage of waste rock and about 200 times the tonnage of mined overburden, depending on the local geology. Leachate produced by unneutralized or uncontained mine wastes is a threat to surface and groundwater.

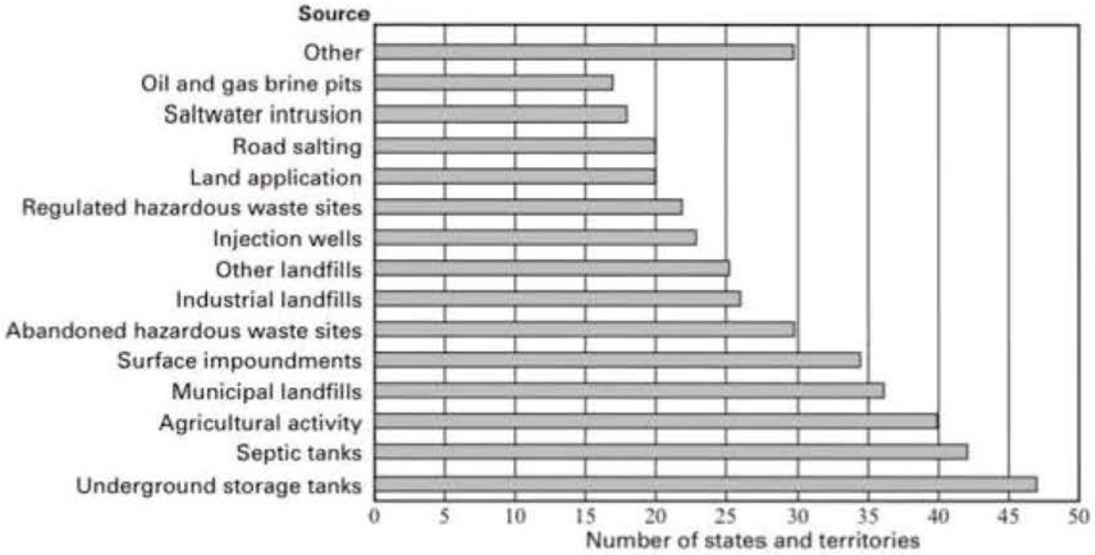
In some cases, *in situ* leach mining is used instead of physical removal of ore-containing rock. In these instances, a chemical mobilizing agent called a lixiviant is pumped down a well where it flows into an ore-bearing formation. After ore is dissolved, the pregnant solution circulating underground is removed using extraction wells. Problems can arise with *in situ* leach mining as the geologic structures associated with many ore

1.6 Relative Ranking of Groundwater-Contamination Sources and Substances

Every site of groundwater contamination is unique in its geology, contaminant mixtures, surrounding human-made structures, and pollutant sources. Therefore the risks associated with different localities and their contaminants can vary greatly, and the approaches for site characterization and remediation are typically tailored to each individual site. Although there are many potential sources of groundwater contamination, some pose much more of a threat to groundwater than others. Section 305(b) of the Federal Clean Water Act requires individual States in the U.S. to submit reports to the Environmental Protection Agency on the sources of groundwater contamination in the state and the type of contaminants observed. The data submitted were used to compile *National Water Quality Inventory—1988 Report to Congress* (U.S. EPA 1990).

The states indicated all the groundwater-contamination sources that they considered to be major threats to groundwater in their state. Figure 1.3 shows that more than half the states and territories listed underground storage tanks, septic tanks, agricultural activities, municipal landfills, and abandoned hazardous-waste sites as major threats to groundwater. Other frequently listed sources include industrial landfills, other landfills, injection wells, regulated hazardous-waste sites, land application, road salt, saltwater intrusion, and brine pits from oil and gas wells.

FIGURE 1.3 Frequency of various contamination sources considered by states and territories of the United States to be major threats to groundwater quality.



Source: UNICEF 2012.

Additionally, every two years the Agency for Toxic Substance and Disease Registry (ATSDR) and the Environmental Protection Agency in the United States prepare a list of hazardous substances most commonly found at facilities on the National Priorities List (NPL), also called the "Superfund" program. The list is a prioritization of harmful substances based on a combination of their frequency of occurrence, their toxicity, and compounds that was denser than water and had limited solubility in water. Large volumes of tar were generated and due to routine leaks and spills, leaking tar storage tanks and deliberate disposal, tar was released into the environment. When some of the plants were decommissioned tanks containing tar were just buried in place. Today many of the former manufactured gas plant sites still have soil and groundwater contamination associated with the tar (Luthy et al. 1994).

1.8 Review of Mathematics and the Flow Equation

1.8.1 Derivatives

Soil-moisture movement, groundwater flow, and solute transport may be described by means of partial differential equations. Thus, a brief review is in order.

If a bicyclist is traveling down a highway, we can measure the time that it takes the rider, who has a flying start, to go from a starting point ($S(t_1)$, or the location at the starting time, (t_1), to a point somewhere down the highway ($S(t_2)$, or the location at elapsed time t_2). If we wish to know the average speed of the rider over this distance, we divide the distance from point $S(t_1)$ to point $S(t_2)$ by the elapsed time, $t_2 - t_1$.

$$\frac{\Delta S}{\Delta t} = \frac{S(t_2) - S(t_1)}{t_2 - t_1} \tag{1.1}$$

The rider will be going more slowly uphill and faster downhill. The average speed will thus include a lot of variation. If we were to measure the rider's speed over a shorter part of the course, there would be less variation in speed. As the length of time over which the distance traveled is measured becomes shorter and shorter, the variation in speed decreases. If the time becomes infinitesimally small—for example, the time that it takes the rider to travel a few microns—we obtain an instantaneous speed. This is known as the **first derivative of distance with respect to time** and is defined by

$$\frac{dS(t_1)}{dt} = \lim_{t \to t_1} \frac{S(t) - S(t_1)}{t - t_1} \tag{1.2}$$

where t is any arbitrary time. Figure 1.4 shows a graph of distance traveled by our bicyclist as a function of time. The slope of the line from time t_1 to time t_2 is the average speed over that part of the highway and is expressed as $\Delta S/\Delta t$. *The instantaneous speed at time* t_1 is the slope of the tangent to the curve at that point, which is expressed as dS/dt.

Note that the slope of distance versus time on Figure 1.4 keeps changing. This reflects the changes in speed that occur as the rider goes up and down hills. As the rider goes over the crest of a hill, he or she will perhaps be going rather slowly. As the rider goes downhill, the velocity will increase. We can compare the crest-of-the-hill velocity with the bottom-of the-hill velocity and see that it has increased. This is a measure of the acceleration that occurs as gravity and the leg muscles of the bicyclist combine to increase speed. Figure 1.5 shows the speed of the rider as he or she goes over a hill. At $t = 0$ the rider is coming over the crest of the hill and the speed is 10 mi/hr. At $t = 30$ sec, when the rider is near the bottom of the hill, the speed is 26 mi/hr. The average rate of change in speed is (26 mi/hr–10 mi/hr)/

FIGURE 1.4 Graph of distance traveled versus time graphically showing speed, which is the first derivative of distance with respect to time.

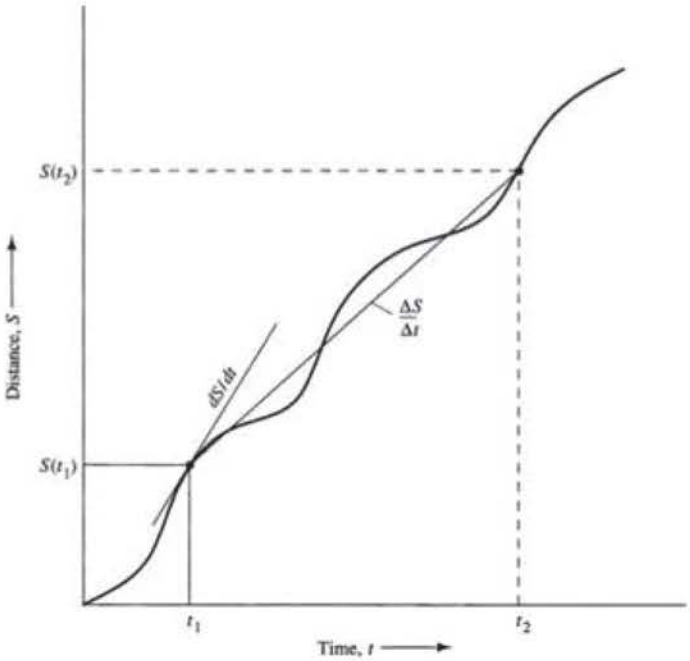
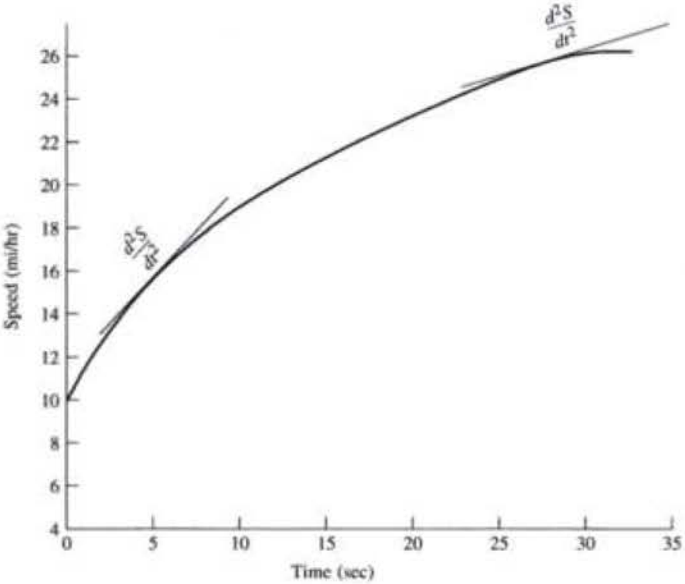


FIGURE 1.5 Graph of speed versus time graphically showing acceleration, which is the second derivative of distance with respect to time.



30 sec, or 0.53 mi/hr/sec. The rate of change is faster near the top of the hill where the slope is steeper and there is less wind resistance, since the rider is moving more slowly. From 0 to 5 sec the speed changes from 10 to 15 mi/hr, or 1.0 mi/hr/sec. Acceleration

is the rate of change of speed with time, which is a second derivative. It is the slope of a tangent to the curve at a given time. It can be expressed as

$$\frac{d\left(\frac{dS}{dt}\right)}{dt} \quad \text{or} \quad \frac{d^2S}{dt^2}$$

The tangent at 5 sec. can be seen to be steeper than the tangent at 30 sec, where the rate of change is less.

In hydrogeology we have many parameters that are a function of more than one independent variable. For example, hydraulic head is a function of the three space variables: $h = h\,(x, y, z)$. We frequently differentiate head with respect to one of the space variables while holding the other two variables constant. Such derivatives of a parameter with respect to a single variable are called **partial derivatives**. The second derivative of hydraulic head with respect to the space variables is

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2}$$

1.8.2 Darcy's Law

The first experimental study of water movement through a porous medium was performed by Henry Darcy (Darcy 1856). He found that the one-dimensional flow of water through a pipe filled with sand was proportional to the cross-sectional area and the head loss along the pipe and inversely proportional to the flow length. Darcy's law can be expressed as

$$Q = -KA\frac{dh}{dl} \tag{1.3}$$

where

Q = volumetric discharge

K = proportionality constant known as hydraulic conductivity

A = cross-sectional area

dh/dl = gradient of hydraulic head

This equation can also be expressed in terms of **specific discharge**, or **Darcy flux**, q, which is the volumetric flow rate, Q, divided by the cross-sectional area, A.

$$q = -K\frac{dh}{dl} \tag{1.4}$$

Darcy's law was obtained for one-dimensional flow. However, as was previously stated, head is a function of all three dimensions: $h = h\,(x, y, z)$.

The hydraulic conductivity is the measure of the ability of the fractured or porous media to transmit water. It can have different values, depending upon the actual direction that the water is flowing through the porous media. In such a case the medium is said to be **anisotropic**. The value of the hydraulic conductivity can be measured in three principle directions, K_x, K_y, and K_z. If the hydraulic conductivity is the same in all directions, then $K_x = K_y = K_z = \mathrm{K}$ and the medium is said to be **isotropic**.

1.8.3 Scalar, Vector, and Tensor Properties of Hydraulic Head and Hydraulic Conductivity

We first need to define some terms relating to **tensors**. A zero-order tensor, also called a **scalar**, is a quantity characterized only by its size or magnitude. Examples in hydrogeology include hydraulic head, chemical concentration, and temperature. A firstorder tensor, or **vector**, is a quantity that has both a magnitude and a direction. Vectors require three components, each having a magnitude and direction. Velocity, specific discharge, mass flux, and heat flux are examples. A second-order tensor—or, simply, **tensor**—acts like the product of two vectors, requiring nine components to account for all possible products of the three components of each vector. Examples in hydrogeology are intrinsic permeability, hydraulic conductivity, thermal conductivity, and hydrodynamic dispersion.

The hydraulic head is a scalar. However, the gradient of the head is a vector as it has both a magnitude and a direction. The gradient of h is designated as grad h:

$$\text{grad } h = i\frac{\partial h}{\partial x} + j\frac{\partial h}{\partial y} + k\frac{\partial h}{\partial z} \tag{1.5}$$

where **i**, **j**, and **k** are unit vectors in the x, y, and z directions. An equivalent notation is the use of the vector differential operator, del, which has the symbol ∇. This operator is equivalent to

$$i\frac{\partial}{\partial x} + j\frac{\partial}{\partial y} + k\frac{\partial}{\partial z} \tag{1.6}$$

Another vector is the specific discharge, **q**. It has three components, q_x, q_y, and q_z, when measured along the Cartesian coordinate axes. Associated with any vector is a positive scalar with a value equal to the magnitude of the vector. If q is the magnitude of the vector **q**, this can be expressed as

$$q = |q| \tag{1.7}$$

A second-order tensor, such as **K**, hydraulic conductivity, can be described by nine components. In matrix form they are expressed as:

$$K = \begin{bmatrix} K_{xx} K_{xy} K_{xz} \\ K_{yx} K_{yy} K_{yz} \\ K_{zx} K_{zy} K_{zz} \end{bmatrix} \tag{1.8}$$

If the tensor is symmetric, $K_{ij} = K_{ji}$; then inspection of (1.8) shows that there are only six independent components of **K**.

If the coordinate system is oriented along the principal axes, the tensor becomes

$$K=\begin{bmatrix} K_{xx} & 0 & 0 \\ 0 & K_{yy} & 0 \\ 0 & 0 & K_{zz} \end{bmatrix} \tag{1.9}$$

For the special case of an isotropic media—that is, the value of **K** does not depend upon the direction in which it is measured—the tensor becomes

$$K=\begin{bmatrix} K & 0 & 0 \\ 0 & K & 0 \\ 0 & 0 & K \end{bmatrix} \tag{1.10}$$

The three components of the specific discharge vector, **q**, are

$$\begin{aligned} q_x &= -K_{xx}\frac{\partial h}{\partial x} - K_{xy}\frac{\partial h}{\partial y} - K_{xz}\frac{\partial h}{\partial z} \\ q_y &= -K_{yx}\frac{\partial h}{\partial x} - K_{yy}\frac{\partial h}{\partial y} - K_{yz}\frac{\partial h}{\partial z} \\ q_z &= -K_{zx}\frac{\partial h}{\partial x} - K_{zy}\frac{\partial h}{\partial y} - K_{zz}\frac{\partial h}{\partial z} \end{aligned} \tag{1.11}$$

For the special case where we orient the axes of the *x, y,* and *z* coordinate system with the three principal directions of anisotropy, **K** is the matrix shown in (1.9) and the three components of the specific discharge vector are

$$\begin{aligned} q_x &= -K_{xx}\frac{\partial h}{\partial x} \\ q_y &= -K_{yy}\frac{\partial h}{\partial y} \\ q_z &= -K_{zz}\frac{\partial h}{\partial z} \end{aligned} \tag{1.12}$$

For an isotropic material, **K** is represented by the matrix in (1.10) and

$$q = -K\frac{\partial h}{\partial x} - K\frac{\partial h}{\partial y} - K\frac{\partial h}{\partial z} \tag{1.13}$$

or

$$q = -K \text{ grad } h \tag{1.14}$$

If we multiply two vectors together and the result is a scalar, then the product is called a **dot product**, or **inner product**. For example, the del operator dotted into a vector yields a scalar, called the **divergence**. Based on grad h, we can find a velocity vector **v** such that the magnitude and direction vary throughout the porous media. If we apply the del operator to **v**, we obtain the following:

$$\nabla \cdot v = \operatorname{div} v = \frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} \tag{1.15}$$

If we apply the del operator to grad h, the result is the second derivative of head:

$$\nabla \cdot \operatorname{grad} h = \frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} \tag{1.16}$$

1.8.4 Derivation of the Flow Equation in a Deforming Medium

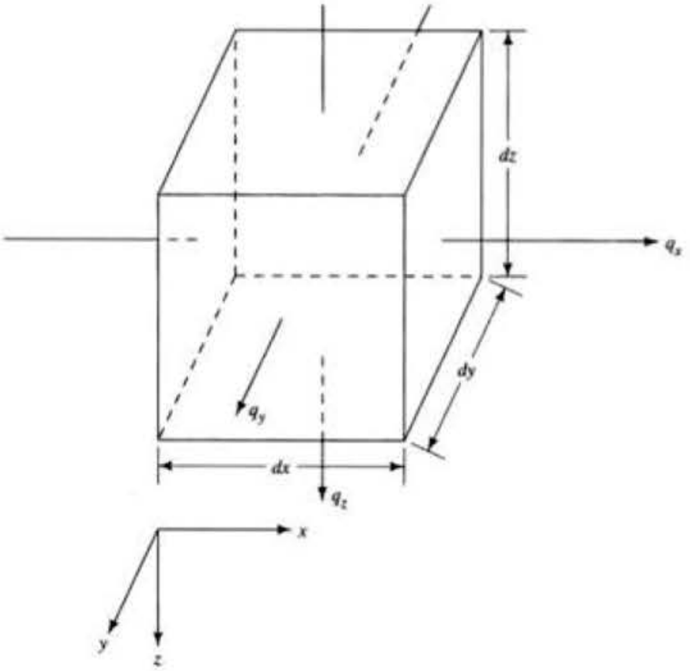
The **law of mass conservation** states that there can be no net change in the mass of fluid in a small representative elementary volume (REV) of a porous medium. In other words, the mass entering the REV less the mass leaving the REV is equal to the change in mass storage with time.

The representative elementary volume is shown on Figure 1.6. The three sides have length dx, dy, and dz, respectively. The area of the two faces normal to the x axis is $dy\,dz$, the area of the faces normal to the y axis is $dx\,dz$, and the area of the faces normal to the z axis is $dx\,dy$.

The component of mass flux into the REV parallel to the x axis is the fluid density times the flux rate:

$$\text{Mass influx along } x \text{ axis} = p_w q_x \, dy \, dz \tag{1.17}$$

FIGURE 1.6 Representative elementary volume for fluid flow.



where

p_w = fluid density (M/L^3)
q_x = specific discharge or volume of flow per cross-sectional area (L/T)
$dy\,dz$ = cross-sectional area (L^2)

The units of mass inflow are mass per unit time (M/T).*

The mass outflow rate will be different than the inflow rate and can be given as:

$$\text{Mass outflow rate parallel to } x \text{ axis} = \left[p_w q_x + \frac{\partial(p_w q_x)dx}{\partial x} \right] dy\,dz \qquad \textbf{(1.18)}$$

The net mass accumulation within the control volume due to the flow component parallel to the *x* axis is the mass inflow minus the mass outflow, or

$$\frac{-\partial(p_w q_x)dx\,dy\,dz}{\partial x}$$

Similar terms exist for the net mass accumulation due to flow components parallel to the *y* and *z* axes:

$$\frac{-\partial(p_w q_y)dy\,dx\,dz}{\partial y}$$

$$\frac{-\partial(p_w q_z)\,dz\,dx\,dy}{\partial z}$$

These three terms can be summed to find the total net mass accumulation within the control volume.

$$-\left[\left(\frac{\partial}{\partial x}(p_w q_x) + \frac{\partial}{\partial y}(p_w q_y) + \frac{\partial}{\partial z}(p_w q_z\right)\right] dx\,dy\,dz \qquad \textbf{(1.19)}$$

The mass of water in the REV, *M*, is the density of water, p$_w$, times the porosity, *n*, times the volume, *dx dy dz*. The change in mass with respect to time is

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial t}(p_w n\,dx\,dy\,dz) \qquad \textbf{(1.20)}$$

From the law of conservation of mass, Equation 1.19 must equal Equation 1.20.

$$-\left[\frac{\partial}{\partial x}(p_w q_x) + \frac{\partial}{\partial y}(p_w q_y) + \frac{\partial}{\partial z}(p_w q_z)\right] dx\,dy\,dz = \frac{\partial}{\partial t}(p_w n)\,dx\,dy\,dz \qquad \textbf{(1.21)}$$

---

* The units of a variable can be expressed in terms of their fundamental dimensions. These are length, L, mass, M, and time, T. The fundamental dimensions for density are mass per unit volume. Volume is length cubed, so the shorthand expression for the fundamental dimensions of density is M/L^3. Specific discharge has the dimensions of velocity, so the fundamental dimensions are L/T, and area has fundamental dimensions of L^2.

We can assume that although density of the fluid may change with time, at any given time it will be the same everywhere in the **REV**. Under this assumption Equation 1.21 can be simplified to

$$-\left[\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}+\frac{\partial q_z}{\partial z}\right]=\frac{1}{p_w}\frac{\partial}{\partial t}(p_w n) \tag{1.22}$$

We may substitute Darcy's law for the specific discharge components given on the left side. If the *xyz* coordinate system is aligned with the principal axes of anisotropy, then Equation 1.12 may be used, and the left side of Equation 1.22 becomes

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) \tag{1.23}$$

The change in mass within the REV is due to changes in the porosity and the density of water as the head changes with time. Thus the change in the volume of water in storage is proportional to the change in head with time. The right side of Equation 1.22 can be expressed as a proportionality constant, *Ss*, the specific storage, times the change in head with time.

$$\frac{1}{p_w}\frac{\partial}{\partial t}(p_w n)=S_s\frac{\partial h}{\partial t} \tag{1.24}$$

Combining Equations 1.22, 1.23, and 1.24 we obtain the main equation for transient flow in an anisotropic medium when the coordinate system is oriented along the principal axes of anisotropy:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)=S_s\frac{\partial h}{\partial t} \tag{1.25}$$

1.8.5 Mathematical Notation

In del and tensor notation Equation 1.25 becomes

$$\nabla\cdot K\cdot\nabla h=S_s\frac{\partial h}{\partial t} \tag{1.26}$$

Another form of expression is called Einstein's summation notation. For example, Darcy's law in the familiar, one-dimensional form is

$$q=-K\frac{dh}{dl} \tag{1.27}$$

It is implied in the preceding equation that the specific discharge is parallel to the direction of dh/dl and that the medium is isotropic. In a more general form, specific discharge, **q**, is a vector with components q_1, q_2, and q_3. Grad h is a vector that we will call **h**. This vector also has components h_1, h_2, and h_3. Hydraulic conductivity, **K**, is a tensor with nine components. To describe Darcy's law in the most general form, we need three equations.

$$q_1 = K_{11}h_1 + K_{12}h_2 + K_{13}h_3 \tag{1.28a}$$

$$q_2 = K_{21}h_1 + K_{22}h_2 + K_{23}h_3 \tag{1.28b}$$

$$q_3 = K_{31}h_1 + K_{32}h_2 + K_{33}h_3 \tag{1.28c}$$

The inner product can be expressed in index notation as

$$q_i = \sum_j K_{ij}h_i \quad (i, j = 1,2,3) \tag{1.29}$$

In Einstein's summation notation, the Σ is dropped with the understanding that the summation is over the repeated indices:

$$q_i = K_{ij}h_j \quad (i, j = 1,2,3) \tag{1.30}$$

In vector notation this can be expressed as either

$$q = K \cdot \text{grad}\, h \tag{1.31}$$

$$q = K \cdot h \tag{1.32}$$

In del notation this is

$$q = K \cdot \nabla h \tag{1.33}$$

In general, we will use the standard form of differential equations rather than any of the shorthand notation. However, the literature cited in this text often uses the compact forms and the reader should be aware of them.

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2

Mass Transport in Saturated Media

2.1 Introduction

In this chapter we will consider the transport of solutes dissolved in groundwater. This is known as **mass** or **solute transport**. The methods presented in this chapter are based on partial differential equations for dispersion that have been developed for homogeneous media (Ogata and Banks 1961; Ogata 1970; Bear 1972; Bear and Verruijt 1987). These equations are similar in form to the familiar partial differential equations for fluid flow. Since those pioneering developments, much work has been done on the theories of mass transport in response to the great interest in problems of groundwater contamination (e.g., Bedient et al. 1994; Zhang and Bennett 1997; Grathwohl 1998; Domenico and Schwartz 1998; Yoram 2003; Yeh et al. 2015; Essaid et al. 2015). One of the outcomes has been the development of what is essentially a new branch of subsurface hydrology, where the flow of fluid and solutes is treated by statistical models; these models can account for the role of varying hydraulic conductivity and other spatially variable hydraulic parameters that accompany aquifer heterogeneity.

Many of the contaminant transport and fate concepts discussed in this chapter were developed based on tracer tests conducted in the field and at the laboratory scale. While a discussion of how tracer tests should be conducted and how the data can be interpreted is beyond the scope of this book, there are ample references and textbooks devoted to this topic (e.g., Davis et al. 1980; U.S. EPA 1985; Payne et al. 2008; Leibundgut et al. 2009; Suthersan et al. 2014).

2.2 Transport by Concentration Gradients

A solute in water will move from an area of greater concentration toward an area where it is less concentrated. This process is known as **molecular diffusion**, or **diffusion**. Diffusion will occur as long as a concentration gradient exists, even if the fluid is not moving. The mass of fluid diffusing is proportional to the concentration gradient, which can be expressed as **Fick's first law**; in one dimension, Fick's first law is

$$F = -D_d\left(dC / dx\right) \qquad \textbf{(2.1)}$$

where

F = mass flux of solute (M/L^2T) per unit area per unit time

D_d = diffusion coefficient (L^2/T)

TABLE 2.1 Diffusion coefficients in water.

Cations		
H^+	9.31×10^{-9} m²/sec	1.00×10^{-7} ft²/sec
Na^+	1.33×10^{-9} m²/sec	1.43×10^{-8} ft²/sec
K^+	1.96×10^{-9} m²/sec	2.11×10^{-8} ft²/sec
Rb^+	2.06×10^{-9} m²/sec	2.22×10^{-8} ft²/sec
Cs^+	2.07×10^{-9} m²/sec	2.23×10^{-8} ft²/sec
Mg^{2+}	7.05×10^{-10} m²/sec	7.59×10^{-9} ft²/sec
Ca^{2+}	7.93×10^{-10} m²/sec	8.54×10^{-9} ft²/sec
Sr^{2+}	7.94×10^{-10} m²/sec	8.55×10^{-9} ft²/sec
Ba^{2+}	8.48×10^{-10} m²/sec	9.13×10^{-9} ft²/sec
Ra^{2+}	8.89×10^{-10} m²/sec	9.57×10^{-9} ft²/sec
Mn^{2+}	6.88×10^{-10} m²/sec	7.41×10^{-9} ft²/sec
Fe^{2+}	7.19×10^{-10} m²/sec	7.74×10^{-9} ft²/sec
Cr^{3+}	5.94×10^{-10} m²/sec	6.39×10^{-9} ft²/sec
Fe^{3+}	6.07×10^{-10} m²/sec	6.53×10^{-9} ft²/sec
Anions		
OH^-	5.27×10^{-9} m²/sec	5.67×10^{-8} ft²/sec
F^-	1.46×10^{-9} m²/sec	1.57×10^{-8} ft²/sec
$C1^-$	2.03×10^{-9} m²/sec	2.19×10^{-8} ft²/sec
Br^-	2.01×10^{-9} m²/sec	2.16×10^{-8} ft²/sec
HS^-	1.73×10^{-9} m²/sec	1.86×10^{-8} ft²/sec
HCO_3^-	1.18×10^{-9} m²/sec	1.27×10^{-8} ft²/sec
SO_4^{2-}	1.07×10^{-9} m²/sec	1.15×10^{-8} ft²/sec
CO_3^{2-}	9.55×10^{-10} m²/sec	1.03×10^{-8} ft²/sec
Organic Compounds		
Tetrachloroethene (PCE)*	7.5×10^{-10} m²/sec	8.07×10^{-9} ft²/sec
Trichloroethene (TCE)*	8.3×10^{-10} m²/sec	8.93×10^{-9} ft²/sec
1,1,1,-Trichloroethane (TCA)*	8.0×10^{-10} m²/sec	8.61×10^{-9} ft²/sec
Benzene**	9.0×10^{-10} m²/sec	9.69×10^{-9} ft²/sec
Toluene**	8.0×10^{-10} m²/sec	8.61×10^{-9} ft²/sec
Ethylbenzene**	7.2×10^{-10} m²/sec	7.75×10^{-9} ft²/sec
1,4-Dioxane***	1.6×10^{-9} m²/sec	1.72×10^{-8} ft²/sec

Source: Y.-H. Li and S. Gregory, 1974. Diffusion of ions in sea water and in deep-sea sediments. Geochemica et Cosmochemica Acta, Vol. 38. © 1974, with the kind permission of Elsevier Science. *Cohen and Mercer, 1993; **U.S.EPA, 2015; ***Mohr 2010. Diffusion coefficients of ions at 25°C; organic compounds are in pure water at 20°C.

C = solute concentration (M/L^3)

dC/dx = concentration gradient ($M/L^3/L$)

The negative sign indicates that the movement is from areas of greater concentration to those of lesser concentration. Values of D_d for ions and select organic compounds in water at 25°C can be found in Table 2-1. They do not vary much with concentration, but they are somewhat temperature-dependent, being about 50% less at 5°C (Robinson and Stokes 2002). The values of D_d are only applicable when studying diffusion in aqueous systems. For systems where the concentrations are changing with time, **Fick's second law** applies. In one dimension this is

$$\partial C / \partial t = D_d \, \partial^2 C / \partial x^2 \tag{2.2}$$

where $\partial C / \partial t$ = change in concentration with time ($M/L^3/T$).

In porous media, diffusion cannot proceed as fast as it can in water because the ions must follow longer pathways as they travel around mineral grains. To account for this, an effective diffusion coefficient, D^*, must be used.

$$D^* = \omega D_d \tag{2.3}$$

where ω is a coefficient that is related to the tortuosity (Bear 1972). **Tortuosity** is a measure of the effect of the shape of the flowpath followed by water molecules in a porous media. If L is the straight-line distance between the ends of a tortuous flowpath of length L_e, the tortuosity, T, can be defined as $T = L_e/L$. Tortuosity in a porous media is always greater than 1, because the flowpaths that water molecules take must diverge around solid particles. Flowpaths across a representative sample of a well-sorted sediment would tend to be shorter than those across a poorly sorted sediment in which the smaller grains were filling the voids between the larger grains. Thus the well-sorted sediment would tend to have a lower value for tortuosity than the poorly sorted sediment. (Tortuosity has also been defined as $(L/L_e)^2$ (Carman 1997; Bear 1972). With this definition, tortuosity always has a value less than 1. This definition will not be used in this text.)

The value of ω, which is always less than 1, can be found from diffusion experiments in which a solute is allowed to diffuse across a volume of a porous medium. Perkins and Johnson (1963) found that ω was equal to 0.7 for sand column studies using a uniform sand. For laboratory studies using limestone and sandstone cores, Boving and Grathwohl (2001) found that ω ranges from 0.35 to 0.098 and that ω is related to the porosity, n, of these rocks by:

$$\omega = n^{-1.2}$$

Diffusion will cause a solute to spread away from the place where it is introduced into a porous medium, even in the absence of groundwater advective flow. Figure 2.1 shows the distribution of a solute introduced at concentration C_0, at time t_0, over an interval $(x - a)$ to $(x + a.)$ At succeeding times t_1 and t_2, the solute has spread out, resulting in a lower concentration over the interval $(x - a)$ to $(x + a)$ but increasing concentrations outside of this interval.

The solute concentration follows a normal, or Gaussian, distribution and can be described by two statistical properties, the mean, C and variance, σ_c^2, which are defined in Section 2.12.2.

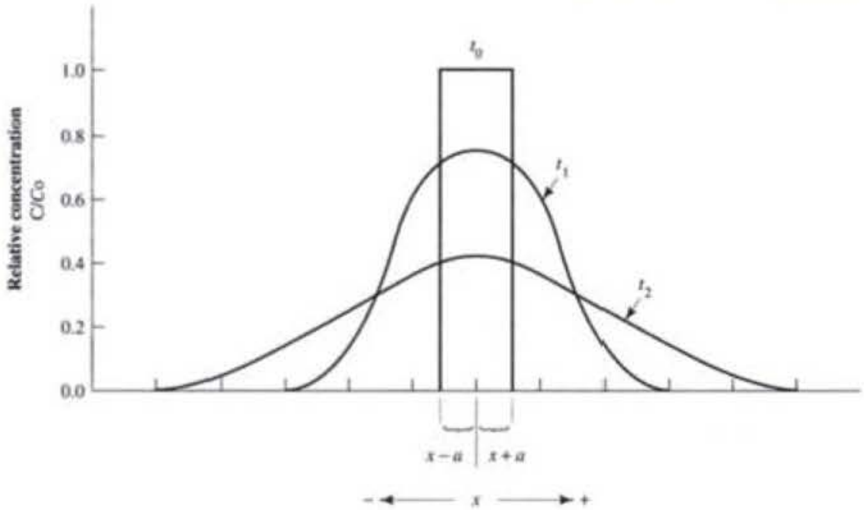
The effective diffusion coefficient, D^*, can be defined as (De Josselin and De Jong 1958)

$$D^* = \frac{\sigma_c^2}{2t} \tag{2.4}$$

This is an alternative definition of effective diffusion coefficient to the one given in Equation 2.3.

The process of diffusion is complicated by the fact that the ions must maintain electrical neutrality as they diffuse. If we have a solution of NaCl, the Na^+ cannot diffuse faster than the Cl^- unless there is some other negative ion in the region into which the Na^+ is diffusing. If the solute is adsorbed onto the mineral surfaces of the porous medium, the net rate of diffusion will be obviously less than for a nonadsorbed species.

Figure 2.1 Spreading of a solute slug with time due to diffusion. A slug of solute was injected into the aquifer at time t_0 with a resulting initial concentration of C_0.



Diffusion can occur when the concentration of a chemical species is greater in one stratum than in an adjacent stratum. For example, solid waste containing a high concentration of chloride ion may be placed directly on the clay liner of a landfill. The concentration of chloride in the leachate contained in the solid waste is so much greater than the concentration of chloride in the pore water of the clay liner that the latter may be considered to be zero as a simplifying assumption in determining a conservative estimate of the maximum diffusion rate. If the solid waste and the clay are both saturated, the chloride ion will diffuse from the solid waste, where its concentration is greater, into the clay liner, even if there is no fluid flow. The concentration of chloride in the solid waste, C_0, will be assumed to be a constant with time, as it can be replaced by dissolution of additional chloride. The concentration of chloride in the clay liner, $C_i(x, t)$, at some distance x from the solid waste interface and sometime t after the waste was placed, can be determined from Equation 2.5 (Crank 1956). This is a solution to Equation 2.2 for the appropriate boundary and initial conditions.

$$C_i(x,t) = C_0 \operatorname{erfc} \frac{x}{2\left(D^* t\right)^{0.5}} \qquad \textbf{(2.5)}$$

where

C_i = the concentration at distance x from the source at time t since diffusion began

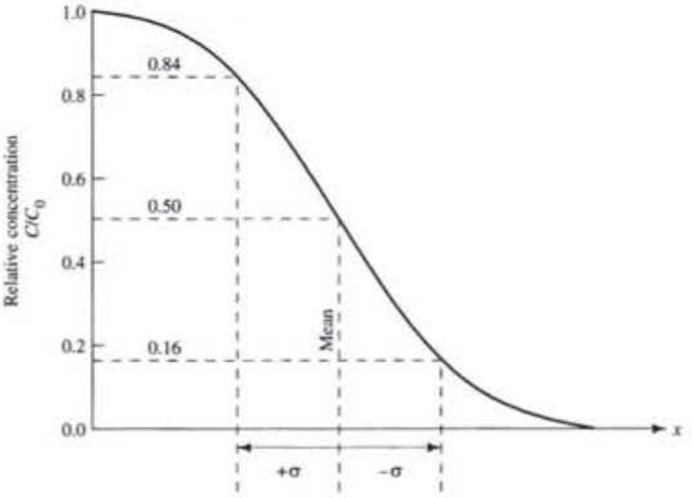
C_0 = the original concentration, which remains a constant

erfc = the complementary error function (Appendix A)

The complementary error function, erfc, is a mathematical function that is related to the normal, or Gaussian, distribution. This means that the solution described by Equation 2.5 is normally distributed, as is expected for a diffusional process. Figure 2.2

shows the profile of relative concentration for a solute diffusing from a region where the concentration is C_0 to a region where it was initially zero. Because the profile is normally distributed, 84% of the values will be less than the value that is one standard deviation more than the mean and 16% of the values will be less than the value that is one standard deviation less than the mean. The standard deviation is the square root of the variance.

Figure 2.2 The profile of a diffusing front as predicted by the complementary error function.



The complementary error function is tabulated in Appendix A or it can be calculated in the spreadsheet program Excel using the syntax: ERFC(x). It is related to the error function, erf, by

$$\operatorname{erfc}(B) = 1 - \operatorname{erf}(B)$$

The value of erfc(B) is 0 for all positive values of B greater than 3.0 and 1.0 for a B of 0. For some applications it may be necessary to find erfc of a negative number. Appendix A does not give values for erfc(B) for negative values of B. These must be computed from the relationship

$$\operatorname{erfc}(-B) = 1 + \operatorname{erf} B$$

The error function, erf(B) is defined as:

$$\operatorname{erf}(B) = \frac{2}{\sqrt{\pi}} \int_0^B e^{-t^2}\, dt$$

The above equation cannot be solved analytically. However, it is tabulated in Appendix A. It can also be approximated by the analytical expression:

$$\operatorname{erf}(B) = \sqrt{1 - \exp\left(\frac{-4B^2}{\pi}\right)}$$

Thus values of erfc(B) range from 0 to +2, since the maximum value of erf(B) is 1.0 for 3.0 and all greater numbers.

EXAMPLE PROBLEM

Assume a D of 1×10^{-9} m^2/sec and an ω of 0.5, to give a D^* of 5×10^{-10}m^2/sec. Find the value of the concentration ratio, C_i/C_0, at a distance of 5m after 100 yr of diffusion.

1. Convert 100 yr to seconds:

$$100\text{yr} \times 365\text{da/yr} \times 1440\text{ min/da} \times 60\text{ sec/min} = 3.15 \times 10^9\text{ sec}$$

2. Insert values into Equation 2.5:

$$\frac{C_i}{C_0} = \text{erfc}\frac{5}{2(5 \times 10^{-10}\text{m}^2/\text{sec} \times 3.15 \times 10^9\text{ sec})^{0.5}}$$

3. Solve:

$$\frac{C_i}{C_0} = \text{erfc}\left(\frac{5}{2.51}\right) = \text{erfc } 1.99 = 0.005$$

In 100 yr, diffusion over a 5-m distance would yield a concentration that is 0.5% of the original.

From the preceding example problem it is obvious that diffusion is not a particularly rapid means of transporting dissolved solutes. Diffusion is the predominant mechanism of transport only in low-permeability hydrogeologic regimes. However, it is possible for solutes to move through a porous or a fractured medium by diffusion even if the groundwater is not flowing.

■ 2.3 Transport by Advection

Dissolved solids are carried along with the flowing groundwater. This process is called **advective transport,** or **advection.** The amount of solute that is being transported is a function of its concentration in the groundwater and the quantity of the groundwater flowing. For one-dimensional flow normal to a unit cross-sectional area of the porous media, the quantity of water flowing is equal to the *average linear velocity* times *the effective porosity.* **Average linear velocity**, v_x, is the rate at which the flux of water across the unit cross-sectional area of pore space occurs. It is not the average rate at which the water molecules are moving along individual flowpaths, which is greater than the average linear velocity due to tortuosity. The **effective porosity**, n_e, is the porosity through which flow can occur. Noninterconnected and dead-end pores are not included in the effective porosity, so that $n_e < n$.

$$v_x = \frac{K}{n_e}\frac{dh}{dl} \tag{2.6}$$

where

v_x = average linear velocity (L/T)
K = hydraulic conductivity (L/T)

n_e = effective porosity
dh/dl = hydraulic gradient (L/L)

Note that the abbreviation n is used in the context of flow and transport under saturated conditions. When discussing unsaturated flow, θ is preferred because it refers to the water content of the porous matrix, as defined in Chapter 4. When the matrix is fully saturated n equals θ. The one-dimensional mass flux, F_x, due to advection is equal to the quantity of water flowing times the concentration of dissolved solids and is given by Equation 2.7:

$$F_x = v_x n_e C \tag{2.7}$$

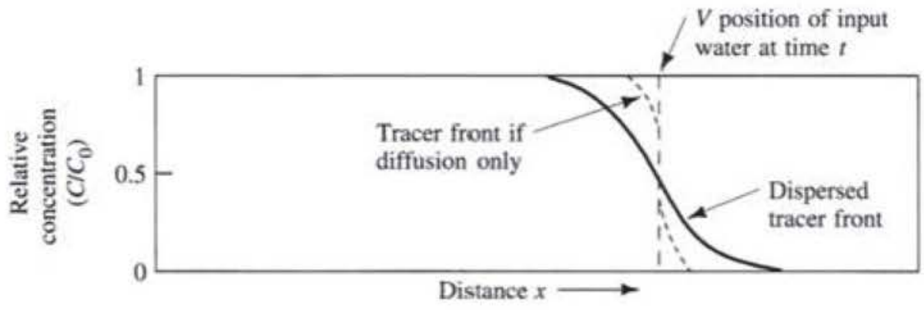
The one-dimensional advective transport equation is

$$\frac{\partial C}{\partial t} = -v_x \frac{\partial C}{\partial x} \tag{2.8}$$

(The derivation of this equation is given in Section 2.6.)

Solution of the advective transport equation yields a sharp concentration front. On the advancing side of the front, the concentration is equal to that of the invading groundwater, whereas on the other side of the front it is unchanged from the background value. This is known as **plug flow**, with all the pore fluid being replaced by the invading solute front. The sharp interface that results from plug flow is shown in Figure 2.3. The vertical dashed line at V represents an advancing solute front due to advection alone.

Figure 2.3 Advective transport and the influence of longitudinal dispersion and diffusion on the transport of a solute in one-dimensional flow.



Source: C.W. Fetter. 1994. *Applied Hydrogeology*, 3rd ed. Upper Saddle River, New Jersey: Prentice-Hall, Inc.

Due to the heterogeneity of geologic materials, advective transport in different strata can result in solute fronts spreading at different rates in each stratum. If one obtains a sample of water for purposes of monitoring the spread of a dissolved contaminant from a borehole that penetrates several strata, the water sample will be a composite of the water from each stratum. Due to the fact that advection will transport solutes at different rates in each stratum, the composite sample may be a mixture of water containing the transported solute coming from one stratum and uncontaminated groundwater coming from a different stratum where the average linear velocity is lower. The concentration of the contaminant in the composite sample would thus be less than in the source.

EXAMPLE PROBLEM

Dissolved nitrate in a concentration of 18.0 mg/L is being advected with flowing groundwater at a velocity of 0.331 m/day in an aquifer with a porosity of 0.225. Groundwater from the aquifer discharges into a stream. What is the mass flux of nitrate into the stream if the aquifer is 1.80 m thick and 123 m wide where it discharges into the stream?

From Equation 2.7 the one dimensional mass flux is

$F_x = v_x n_e C$

Given: $v_x = 0.331$ m/da

$n_e = 0.225$

$C = 18.0$ mg/L

For consistent units the concentration should be in gm/m^3.

$C = 18.0 \text{ mg/L} \times 1/1000 \text{ gm/mg} \times 1000 \text{ L/m}^3$

$C = 18.0 \text{ gm/m}^3$

The one dimensional mass flux is:

$F_x = 0.331 \text{ m/da} \times 0.225 \times 18.0 \text{ gm/m}^3$

$F_x = 1.34 \text{ gm/da-m}^2$

The flux into the stream is the one dimensional mass flux times the cross sectional area where the aquifer discharges into the stream.

Total flux = $1.34 \text{ gm/da-m}^2 \times 123 \text{ m} \times 1.80 \text{ m}$

Total flux = 297 gm/da

■ 2.4 Mechanical Dispersion

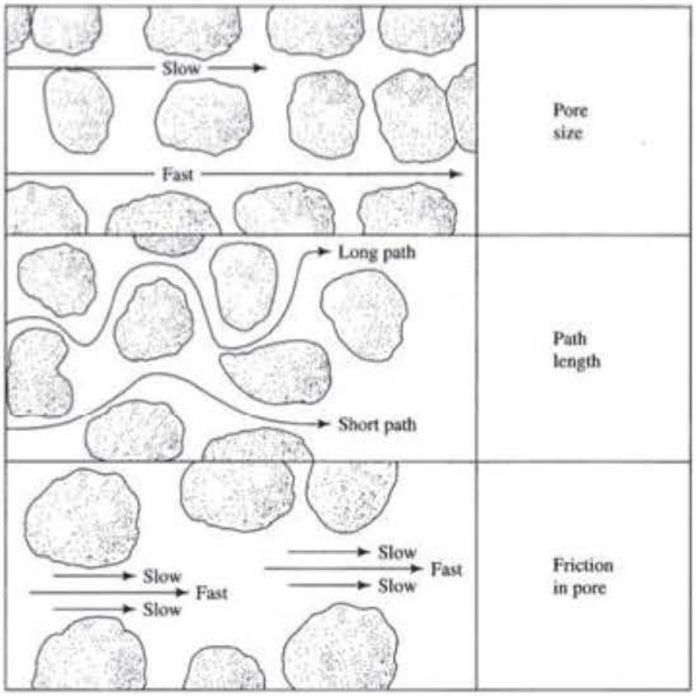
Groundwater is moving at rates that are both greater and less than the average linear velocity. At the macroscopic scale—that is, over a domain including a sufficient volume that the effects of individual pores are averaged (Bear 1972)—there are three basic causes of this phenomenon: (1) As fluid moves through the pores, it will move faster in the center of the pores than along the edges. (2) Some of the fluid particles will travel along longer flow paths in the porous media than other particles to go the same linear distance. (3) Some pores are larger than others, which allows the fluid flowing through these pores to move faster. These factors are illustrated in Figure 2.4.

If all groundwater containing a solute were to travel at exactly the same rate, it would displace water that does not contain the solute and create an abrupt interface between the two waters. However, because the invading solute-containing water is not all traveling at the same velocity, mixing occurs along the flowpath. This mixing is called **mechanical dispersion**, and it results in a dilution of the solute at the advancing edge of flow. The mixing that occurs along the direction of the flowpath is called **longitudinal dispersion**.

An advancing solute front will also tend to spread in directions normal to the direction of flow because at the pore scale the flowpaths can diverge, as shown in Figure 2.5. The result of this is mixing in directions normal to the flow path called **transverse dispersion**.

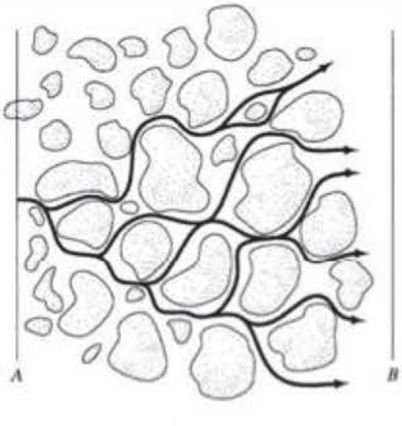
If we assume that mechanical dispersion can be described by Fick's law for diffusion (Equations 2.1 and 2.2) and that the amount of mechanical dispersion is a function of the average linear velocity, then we can introduce a coefficient of mechanical dispersion. This is equal to a property of the medium called *dynamic dispersivity*, or

FIGURE 2.4 Factors causing longitudinal dispersion at the scale of individual pores.



Source: C.W. Fetter. 1994. *Applied Hydrogeology, 3d ed.* Upper Saddle River, New Jersey: Prentice-Hall, Inc.

FIGURE 2.5 Flowpaths in a porous medium that cause lateral (transverse) hydrodynamic dispersion.



Source: C.W. Fetter. 1994. *Applied Hydrogeology, Third Edition.* Upper Saddle River, New Jersey: Prentice-Hall, Inc.

simply *dispersivity*, α, times the average linear velocity. If i is the principle direction of flow, the following definitions apply:

$$\text{Coefficient of longitudinal mechanical dispersion} = \alpha_i v_i \tag{2.9}$$

where

v_i = the average linear velocity in the i direction (L/T)

α_i = the dynamic dispersivity in the i direction (L)

and

$$\text{Coefficient of transverse mechanical dispersion} = \alpha_j v_i \tag{2.10}$$

where

v_i = the average linear velocity in the i direction (L/T)

α_j = the dynamic dispersivity in the j direction (L)

2.5 Hydrodynamic Dispersion

The process of molecular diffusion cannot be separated from mechanical dispersion in flowing groundwater. The two are combined to define a parameter called the **hydrodynamic dispersion coefficient**, D. It is represented by the following formulas:

$$D_L = \alpha_L v_i + D^* \tag{2.11a}$$

$$D_T = \alpha_T v_i + D^* \tag{2.11b}$$

where

D_L = hydrodynamic dispersion coefficient parallel to the principal direction of flow (longitudinal)

D_T = hydrodynamic dispersion coefficient perpendicular to the principal direction of flow (transverse)

α_L = longitudinal dynamic dispersivity

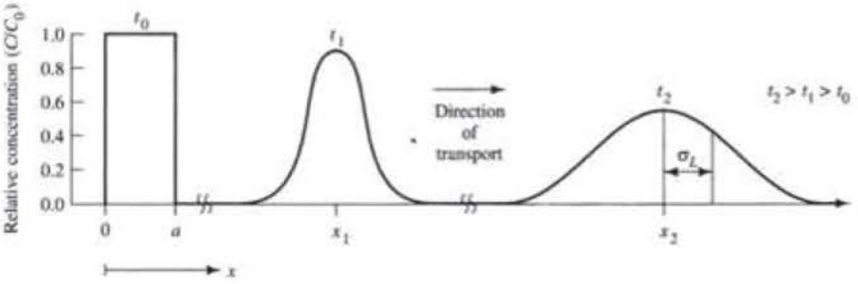
α_T = transverse dynamic dispersivity

Figure 2.3 shows the effect of diffusion and mechanical dispersion on the relative concentration (C/C_0) of a solute acting as a tracer that has been injected into a porous medium under one-dimensional flow conditions. The vertical line at V represents the advective transport without dispersion. Effects of diffusion and mechanical dispersion are shown.

The process of hydrodynamic dispersion can be illustrated by Figure 2.6. A mass of solute is instantaneously introduced into the aquifer at time t_0 over the interval $x = 0 + a$. The resulting initial concentration is C_0. The advecting groundwater carries the mass of solute with it. In the process the solute slug spreads out, so that the maximum concentration decreases with time, as shown for times t_1 and t_2. The diffusional model of hydrodynamic dispersion predicts that the concentration curves will have a Gaussian distribution that is described by the mean and the variance. With this distribution the coefficients of longitudinal and transverse hydrodynamic dispersion can be defined as

$$D_L = \frac{{\sigma_L}^2}{2t} \tag{2.12a}$$

FIGURE 2.6 Transport and spreading of a solute slug with time due to advection and dispersion. A slug of solute was injected at $x = 0 + a$ at time t_0 with a resulting concentration of C_0. The groundwater flow is to the right.



$$D_T = \frac{\sigma_T^{\ 2}}{2t} \tag{2.12b}$$

where

t = time
σ_T^2 = variance of the transverse spreading of the plume
σ_L^2 = variance of the longitudinal spreading of the plume

2.6 Derivation of the Advection-Dispersion Equation for Solute Transport

This derivation of the advection-dispersion equation is based on work by Freeze and Cherry (1979), Bear (1972), and Ogata (1970). Working assumptions are that the porous medium is homogeneous, isotropic, and saturated with fluid and that flow conditions are such that Darcy's law is valid.

The derivation is based on the conservation of mass of solute flux into and out of a small representative elementary volume (REV) of the porous media. The REV is the smallest volume that is representative for the entirety of whole medium. A measurement made at the REV scale will yield a value typically of the whole (Hill 1963). The REV concept serves as a cornerstone in the continuum modeling of transport phenomena in porous media (Bachmat and Bear 1987). The flow is at a macroscopic scale, which means that it accounts for the differences in flow from pore to pore. A representative elementary volume is illustrated in Figure 1.6.

The average linear velocity, v, has components v_x, v_y, and v_z. The concentration of solute, C, is mass per unit volume of solution. Mass of solute per unit volume of aquifer is the product of the effective porosity, n_e, and C. Porosity is considered to be a constant because the aquifer is homogeneous.

The solute will be transported by advection and hydrodynamic dispersion. In the i direction the solute transport is given by

$$\text{Advective transport} = v_i n_e C \, dA \tag{2.13}$$

$$\text{Dispersive transport} = n_e D_i \frac{\partial C}{\partial i} dA \tag{2.14}$$

where dA is the cross-sectional area of the element and the i direction is normal to that cross-sectional face.

The total mass of solute per unit cross-sectional area transported in the i direction per unit time, F_i, is the sum of the advective and the dispersive transport and is given by

$$F_i = v_i n_e C - n_e D_i \frac{\partial C}{\partial i} \tag{2.15}$$

The negative sign indicates that the dispersive flux is from areas of greater to areas of lesser concentration.

The total amount of solute entering the representative elementary volume is

$$F_x\,dz\,dy + F_y\,dz\,dx + F_z\,dx\,dy$$

The total amount of solute leaving the representative elementary volume is

$$\left(F_x + \frac{\partial F_x}{\partial x}dx\right)dz\ dy + \left(F_y + \frac{\partial F_y}{\partial y}dy\right)dz\ dx + \left(F_z + \frac{\partial F_z}{\partial z}dz\right)dx\ dy$$

The difference between the mass of the solute entering the representative elementary volume and the amount leaving it is

$$-\left(\frac{\partial F_x}{\partial x} + \frac{\partial F_y}{\partial y} + \frac{\partial F_z}{\partial z}\right)dx\ dy\ dz$$

The rate of mass change in the representative elementary volume is

$$n_e \frac{\partial C}{\partial t} dx\ dy\ dz$$

By the law of mass conservation, the rate of mass change in the representative elementary volume must be equal to the difference in the mass of the solute entering and the mass leaving.

$$\frac{\partial F_x}{\partial x} + \frac{\partial F_y}{\partial y} + \frac{\partial F_z}{\partial z} = -n_e \frac{\partial C}{\partial t} \tag{2.16}$$

Equation 2.15 can be used to find the values of F_x, F_y, and F_z. These are substituted in Equation 2.16, which becomes, after cancellation of n_e from both sides,

$$\begin{aligned}&\left[\frac{\partial}{\partial x}\left(D_x \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_y \frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(D_z \frac{\partial C}{\partial z}\right)\right]\\ &-\left[\frac{\partial}{\partial x}(v_x C) + \frac{\partial}{\partial y}(v_y C) + \frac{\partial}{\partial z}(v_z C)\right] = \frac{\partial C}{\partial t}\end{aligned} \tag{2.17}$$

Equation 2.17 is the three-dimensional equation of mass transport for a *conservative* solute—that is, one that does not interact with the porous media or undergo biological or radioactive decay.

In a homogeneous medium, D_x, D_y, and D_z do not vary in space. However, because the coefficient of hydrodynamic dispersion is a function of the flow direction, even in an isotropic, homogeneous medium, $D_x \neq D_y \neq D_z$. For those domains where the average linear velocity, v_x, is uniform in space, Equation 2.17 for one-dimensional flow in a homogeneous, isotropic porous media is

$$D_L \frac{\partial^2 C}{\partial x^2} - v_x \frac{\partial C}{\partial x} = \frac{\partial C}{\partial t} \tag{2.18}$$

In a homogeneous medium with a uniform velocity field, Equation 2.17 for two-dimensional flow with the direction of flow parallel to the x axis is

$$D_L \frac{\partial^2 C}{\partial x^2} + D_T \frac{\partial^2 C}{\partial y^2} - v_x \frac{\partial C}{\partial x} = \frac{\partial C}{\partial t} \tag{2.19}$$

where

D_L = the longitudinal hydrodynamic dispersion (L^2/T)
D_T = the transverse hydrodynamic dispersion (L^2/T)

Equation 2.17 for radial flow from a well can be written in polar coordinates (Ogata 1970) as

$$\frac{\partial}{\partial r}\left(D \frac{\partial C}{\partial r}\right) + \frac{D}{r}\frac{\partial C}{\partial r} - u \frac{\partial C}{\partial r} = \frac{\partial C}{\partial t} \tag{2.20}$$

where

r = radial distance to the well
u = average pore velocity of injection, which is found from

$$u = \frac{Q}{2\,\pi\, n_e R r^2}$$

where

Q = the rate of injection into the well
n_e = effective porosity
R = length of well screen or open bore hole

2.7 Diffusion versus Dispersion

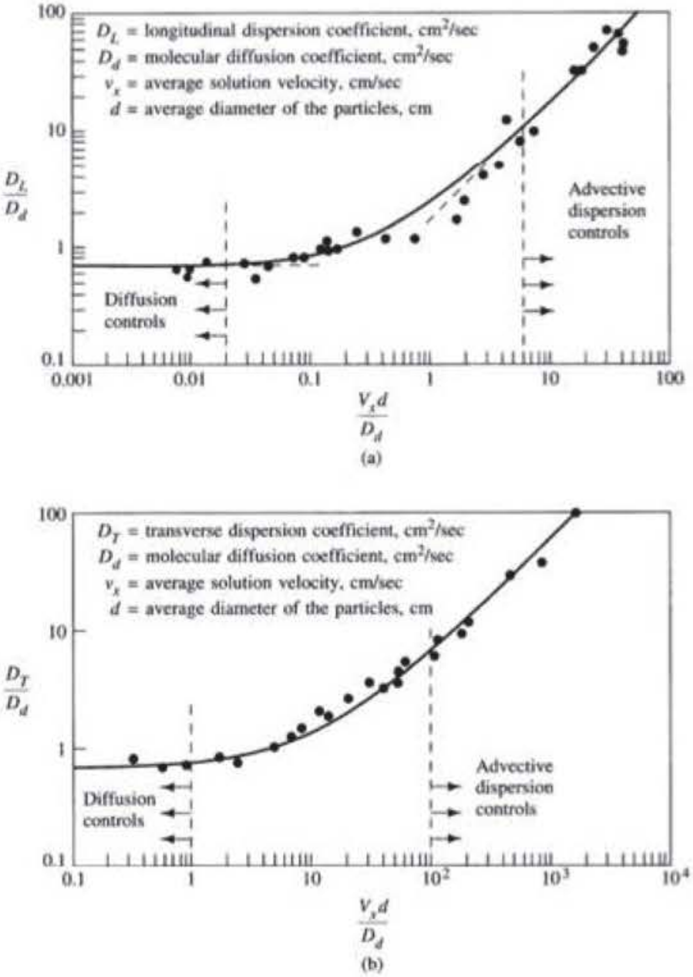
In the previous section the mass transport equation was derived on the basis of hydrodynamic dispersion, which is the sum of mechanical dispersion and diffusion. It would have been possible to separate the hydrodynamic dispersion term into the two components and have separate terms in the equation for them. However, as a practical matter, under most conditions of groundwater flow, diffusion is insignificant and is neglected.

It is possible to evaluate the relative contribution of mechanical dispersion and diffusion to solute transport. A **Peclet number**, P_e, is a dimensionless number that can relate the effectiveness of mass transport by advection to the effectiveness of mass transport by either dispersion or diffusion. Peclet numbers have the general form of $v_x d/D_d$ or $v_x L/D_L$, where v_x is the advective velocity, d and L are characteristic flow lengths, D_d is the coefficient of molecular diffusion, and D_L is the longitudinal hydrodynamic dispersion coefficient. The column Peclet number, which defines the ratio of transport by advection to the rate of transport by molecular diffusion in column studies, is a dimensionless parameter defined as $v_x d/D_d$, where d is the average grain diameter and D_d is the coefficient of molecular diffusion. A plot of the ratio of D_L/D_d versus the Peclet number is given in Figure 2.7a. Shown on this figure are the results of a number of experimental measurements using sand columns and tracers as well as some experimental curves from several investigators (Perkins and Johnson 1963). Delgado (2007) presents empirical correlations for the prediction of the dispersion coefficients (D_T and D_L) based Peclet number and Schmidt number (S_c). The dimensionless Schmidt number relates the viscous diffusion rate to the molecular diffusion rate. S_c is defined as:

$$S_c = \frac{\mu}{\rho D}$$

where μ and ρ are the dynamic viscosity (M/LT) and density of the fluid, respectively. D is the diffusion coefficient.

FIGURE 2.7 Graph of dimensionless dispersion coefficients versus Peclet number, $P_e = v_x d/D_d$. (a) D_L/D_e versus P_e and (b) D_T/D_e versus P_e.



(a)

(b)

Source: T. K. Perkins and O. C. Johnson. 1963. *Society of Petroleum Engineers Journal* 3:70–84. Society of Petroleum Engineers.

At zero flow velocity D_L is equal to D^*, since $D_L = a_L v_x + D^*$. In this manner the value of ω, the tortuosity factor, can be experimentally determined as $D^* = \omega D_d$. At very low velocities, the ratio of D_L/D_d is a constant with a value of about 0.7, which is the experimentally determined value of ω for uniform sand. This shows up on the left side of Figure 2.7(a) as a horizontal line. In this zone diffusion is the predominant force, and dispersion can be neglected. Between a Peclet number of about 0.4 to 6 there is a transition zone, where the effects of diffusion and longitudinal mechanical dispersion are more or less equal.

Figure 2.7(b) shows the plot of D_T/D_d as a function of Peclet number. Although the curve has the same shape as in (a), it occurs at Peclet numbers roughly 100 times greater. This means that diffusion has more control over transverse dispersion at higher Peclet numbers than it does for longitudinal dispersion. Higher Peclet numbers occur with higher velocities and/or longer flow paths. At higher Peclet numbers mechanical dispersion is the predominant cause of mixing of the contaminant plume (Perkins and Johnson 1963; Bear 1972; Bear and Verruijt 1987) and the effects of diffusion can be ignored. Under these conditions D_i can be replaced with $a_i v_i$ in the advection-dispersion equations.

■ 2.8 Moment Analysis

Contaminant hydrogeologists, like other scientists, have to work with a lot of data, such as periodic measurements of pollutant concentrations in monitoring wells or hydraulic values that determine the flow and transport of these pollutants. If writing a report or publishing data in peer reviewed manuscripts, one is expected to back up the significance of the data with a proper statistical analysis. A review of statistical concepts and methods is not the focus of this book, but excellent introductions into groundwater statistics are provided by Helsel and Hirsch (2002) or Interstate Technology and Regulatory Council (2013).

One statistical method, however, that is quite useful for the analysis of contaminant fate and transport data, especially results from laboratory or field-scale tracer tests, warrants a more detailed discussion. The method is known as moment analysis. This method can be an important tool for calculating mass recoveries in tracer experiments, travel velocities of a plume, and the description of the shape of the plume in terms of dispersivity, skewness, and kurtosis. Both temporal and spatial data can be used for this analysis. The relationship between the spatial and temporal moments and the properties of an evolving solute plume are based on work by Aris (1956) and subsequent modifications by Goltz and Roberts (1987), who developed moment concepts for the analysis of three-dimensional solute transport data. The spatial moment technique was utilized by Marle et al. (1967), Ghüven et al. (1984) and Valocchi (1989) to study solute transport in steady horizontal flow in a perfectly stratified aquifer. Valocchi (1990) provides an overview of the usefulness of temporal moment analysis for studying reactive solute transport in aggregated porous media.

The method of moment was employed for the analysis of many natural gradient field tracer tests. For instance, the spatial moments of the bromide tracer distribution were used to calculate the tracer mass, velocity, and dispersivity during the large-scale tracer test at the Canadian Air Force Base (CFB) in Borden, Ontario (Freyberg 1986; Farrell and Woodbury 1994) or the transport of nonreactive and reactive tracers in a sand and gravel aquifer on Cape Cod, Massachusetts (Leblanc et al. 1991; Garabedian et al. 1991) or at the Twin Lake aquifer test site within the property of the Chalk River

Nuclear Laboratories, where in 1982 and 1983 a pulse of groundwater labeled with ^{131}Iodine was injected (Moltyaner and Killey 1988; Moltyaner and Wills 1991).

The analysis of moments ordinarily is accomplished by numerically solving one or more triple integrals of tracer concentration in the three-dimensional space of the test domain (Freyberg 1986; Glotz and Roberts 1987; Valochhi 1989; Garabedian et al. 1991). The absolute moments (M) in three dimensions are defined as follows:

$$M_{j\,k\,n} = \iiint_{-\infty}^{\infty} C x^{j} y^{k} z^{n} dx\, dy\, dz$$

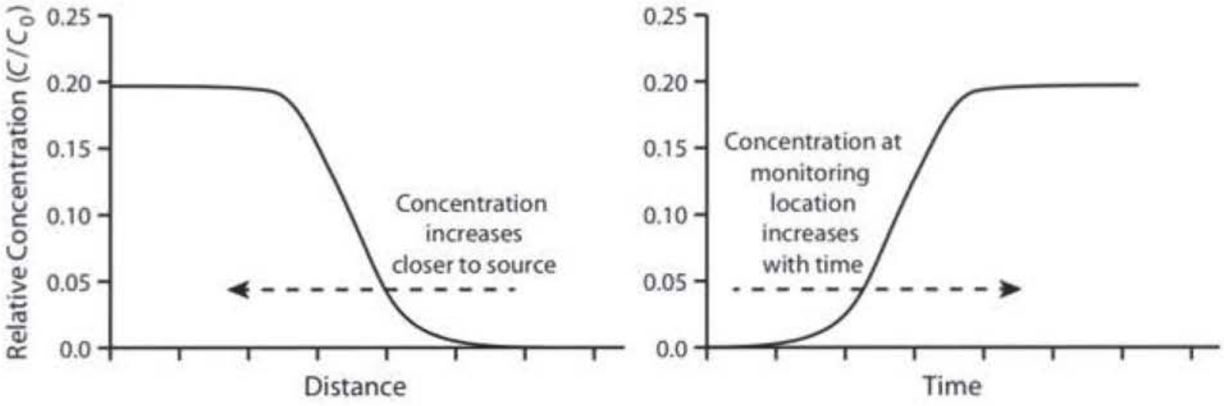
where C is the solute concentration at the spatial coordinates x, y, and z. For one-dimensional data sets, the moment analysis can be simplified to the temporal and spatial forms summarized in Table 2.2.

Temporal moments can be interpreted with the help of breakthrough curves (BTC) (Figure 2.8). A BTC is a graph of concentration versus time. This format of depiction is appropriate when the position of the observer is fixed (Eulerian approach). A BTC

TABLE 2.2 One-dimensional moments.

Moment	Temporal Moments	Spatial Moments
Zeroth Absolute Moment	$M_t^0 = \int_0^\infty C\, dt$	$M_s^0 = \int_0^\infty C\, dx$
First Normalized Moment	$M_t^1 = \dfrac{\int_0^\infty Ct\, dt}{\int_0^\infty C\, dt} = \dfrac{\int_0^\infty Ct\, dt}{M_t^0}$	$M_s^1 = \dfrac{\int_0^\infty Cx\, dx}{\int_0^\infty C\, dx} = \dfrac{\int_0^\infty Cx\, dx}{M_x^0}$
Adjusted First Temporal Moment	$M_{adj}^1 = \dfrac{\int_0^x Ct\, dt}{M_t^0} - \dfrac{1}{2} T_0$	Not defined
Second Central Moment	$M_t^2 = \dfrac{\int_0^\infty \left(t - M_t^1\right)^2 C\, dt}{M_t^0}$	$M_s^2 = \dfrac{\int_0^\infty \left(x - M_s^1\right)^2 C\, dx}{M_s^0}$
Third Central Moment	$M_t^3 = \dfrac{\int_0^\infty \left(t - M_t^1\right)^3 C\, dt}{M_t^0}$	$M_s^3 = \dfrac{\int_0^\infty \left(x - M_s^1\right)^3 C\, dx}{M_s^0}$
Fourth Central Moment	$M_t^4 = \dfrac{\int_0^\infty \left(t - M_t^1\right)^4 C\, dt}{M_t^0}$	$M_s^4 = \dfrac{\int_0^\infty \left(x - M_s^1\right)^4 C\, dx}{M_s^0}$

FIGURE 2.8 Representation of concentration data resulting from a continuous contaminant release scenario: (a) concentration versus distance and (b) concentration versus time. The concentration-time graph is called a breakthrough curve (BTC).



is typically used to report solute concentrations in column effluent during of tracer experiment or at the location of a specific monitoring well. In contrast, a graph of concentration versus distance is not a BTC. It represents a snapshot of concentration data collected more or less simultaneously at various locations within the test domain (Lagrangian approach). Such a graph is useful, for example, for reporting the tracer concentration in groundwater samples collected along the principal axis of a contaminant plume.

It is convenient to normalize the higher order temporal and spatial moments by scaling them to the zeroth temporal moment (M_t^0) or zeroth spatial moment (M_s^0), respectively. Higher moments are centralized by subtracting the first normalized temporal or spatial moment ($M_{t,s}^{\ 1}$) from the elapsed time (t) or distance (x), respectively, since the start of the measurements.

The significance of M_t^0 is that it integrates the area under the concentration versus distance curve (Figure 2.8) and thus presents the mass of solute and a measure for calculating the solute mass recovery and mass balance. The M_s^0 aides in determining the amount of mass passing by a sampling point (i.e., monitoring well). A constant value of M_s^0 at different distances from the origin indicates that no mass loss occurred and therefore suggests a recalcitrance of a compound to sorption of degradation processes. The M_s^1 calculates the mean, i.e., the location of the center of mass of a plume and thus aides in calculating the plume travel velocity. M_t^1 describes the travel time of a dissolved compound (Figure 2.9). While not defined for spatial coordinate data, the adjusted first temporal moment, $M_{adj}^{\ 1}$, is:

$$M^{1}_{adj} = \frac{\int_o^x C\ t\ dt}{M^0} - \frac{1}{2}T_0$$

where T_0 is the pulse length, i.e., the duration of the tracer slug injection. $M_{adj}^{\ 1}$ permits the calculation of the tracer front travel time (Figure 2.11) and therefore $M_{adj}^{\ 1}$ can be used to calculate the retardation factor from the inflection point of the BTC, i.e., where $C/C_{max} = 0.5$. The parameter C_{max} is the maximum concentration measured during the tracer test (Figure 2.9).

FIGURE 2.9 Ideal breakthrough curve (BTC). The arrival time is the time for the center of mass to arrive at the monitoring location. The travel time is the breakthrough time of the tracer front.

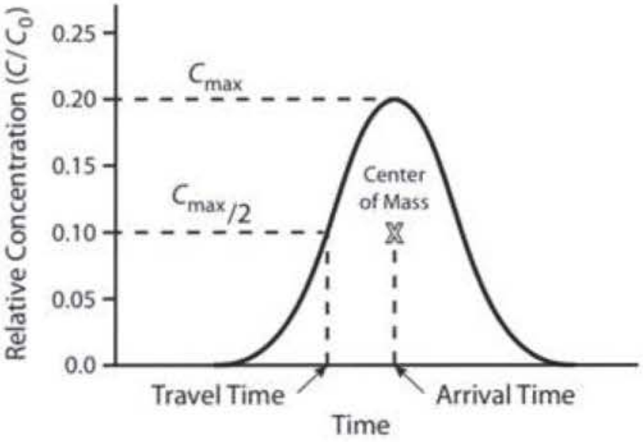
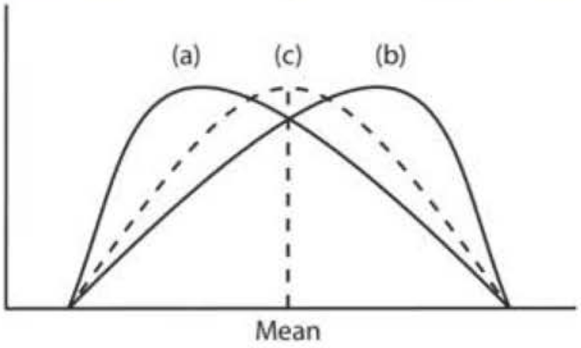


FIGURE 2.10 Skewness: (a) positive, (b) negative and (c) not skewed around the mean ($M^3 = 0$).



The second temporal moment (M_t^2) is the variance (σ^2) and provides a measure for the spread of a plume about the location of the center of mass. The analysis of the second spatial moment (M_s^2) can be used to determine the longitudinal dispersion coefficient, D_L, in either temporal or spatial coordinates:

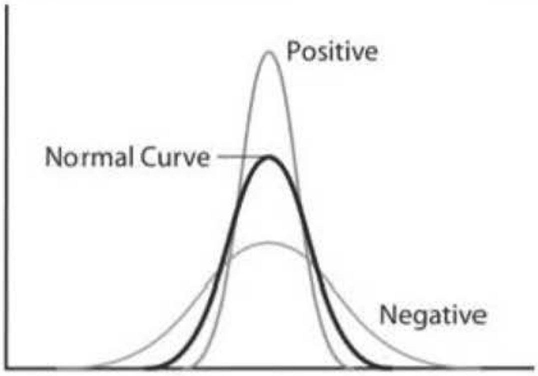
$$D_L = \frac{\sigma_L^2}{2t}$$

$$D_L = \frac{\sigma_L^2 v}{2x}$$

where σ_L^2 is the variance, t is time since the start of the tracer test and v is the linear flow velocity (constant).

The skewness of a curve is described by the third moment (M^3). A positive value indicates that the graph is skewed to the right, whereas a negative value means skewness to the left (Figure 2.10). A value of approximately zero suggests that the data is normally distributed. The fourth moment (M^4) is a measure of kurtosis (Figure 2.11). For a conservative tracer, both M^3 and M^4 should be approximately zero. Deviations

FIGURE 2.11 Negative and positive kurtosis. The M^4 is zero for when the tracer concentration data is normally distributed.



from that value indicate non-ideal transport conditions. Other applications of moment analysis are discussed in Suthersan et al. 2017.

EXAMPLE

A tracer test was conducted and concentration measurements have been collected downgradient from the injection location and at three different times ($t_1 = 30\ d$, $t_2 = 60\ d$, and $t_3 = 90\ d$). Figure 2.12 shows the concentration versus distance data in terms of dimensionless concentration (C/C_0) at three observations points.

In this example, the tracer is nonreactive because the area under the curves (M^0) remains the same for all three data sets. Had the value of M^0 decreased however, it

FIGURE 2.12 The spatial position of the tracer concentrations profiles at times t_1, t_2, and t_3.

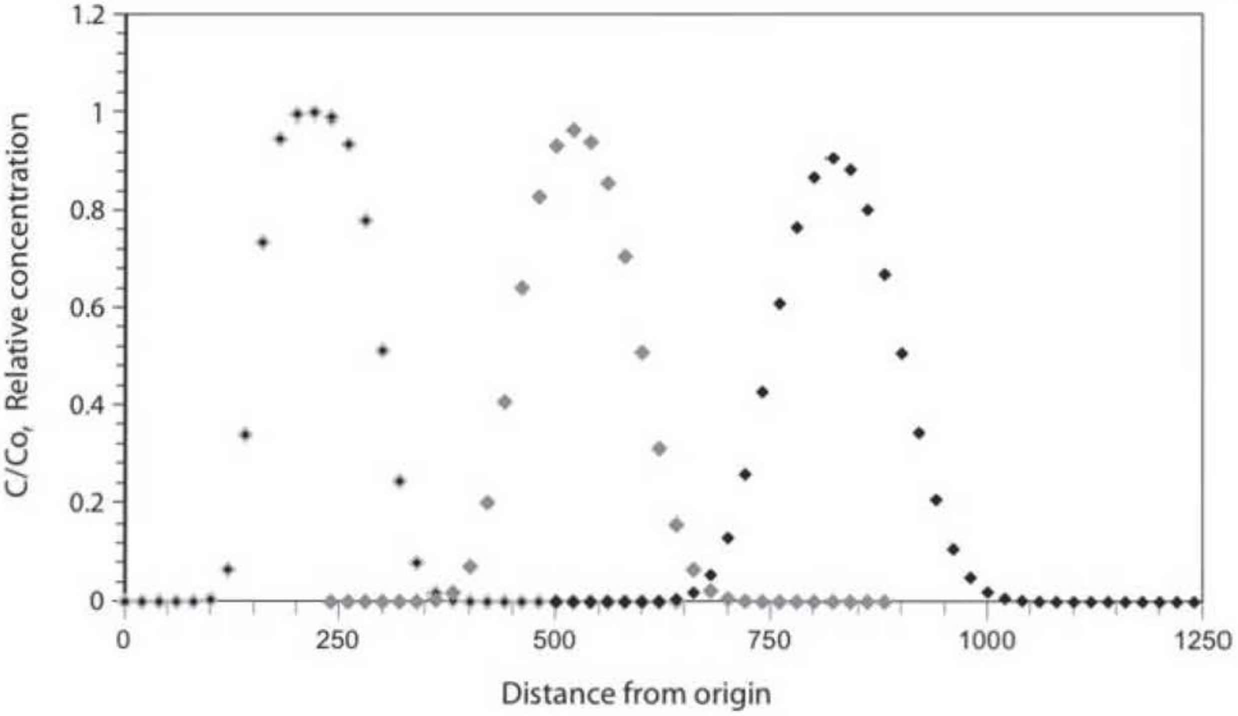
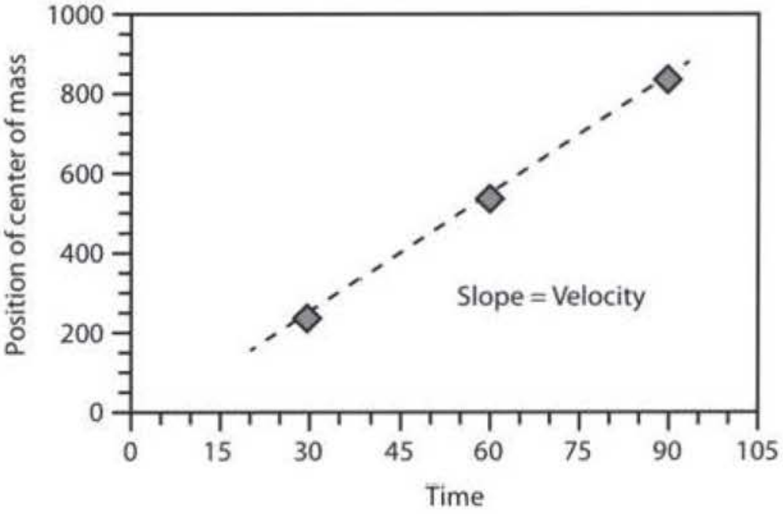


FIGURE 2.13 The velocity of a migrating plume can be estimated from the location of the center of mass (First spatial moment).



would have indicated that a fraction of the tracer was lost during the experiment. In that case, a plot of M^0 versus distance would reveal if the rate of loss is linear or nonlinear.

The velocity of a migrating plume was estimated from the location of the center of mass (M^1) at different times (Figure 2.12). In this example, the velocity remained constant throughout the experiment, which is expected for a nonreactive tracer. If the flow velocity is identical to the groundwater flow velocity, the tracer can be considered "conservative," i.e., its flow is not retarded. By comparing the M^1 of a conservative tracer with that of other tracers that might have been co-injected at the start of the tracer test, one can calculate the relative travel times or relative travel distances and thus the retardation factors for each tracer.

When plotting M^2 for each of the three data sets against the time of measurement, the slope of the regression line is equal to $2D_L$. The M^3 and M^4 values indicate that the three data sets are not skewed and that they do not show kurtosis; once again indicating that the tracer was nonreactive.

2.9 Analytical Solutions of the Advection-Dispersion Equation

2.9.1 Methods of Solution

The advection-dispersion equations can be solved by either numerical or analytical methods. Analytical methods involve the solution of the partial differential equations using calculus based on the initial and boundary value conditions. They are limited to simple geometry and in general require that the aquifer be homogeneous. A number of analytical solutions are presented in this chapter. They are useful in that they can be solved with spreadsheet, like EXCEL, or even a pencil and paper, if one is so inclined.

Numerical methods involve the solution of the partial differential equation by numerical methods of analysis. They are more powerful than analytical solutions in the sense that aquifers of any geometry can be analyzed and aquifer heterogeneities can be accommodated. However, there can be other problems with numerical models, such as numerical errors, which can cause solutions to show excess spreading of solute fronts or plumes that are not related to the dispersion of the tracer that is the subject of the modeling. Bear and Verruijt (1987) present a good introduction to the use of numerical models to solve mass transport equations. These solutions are normally found by methods of computer modeling, a topic beyond the scope of this text. Instead, the reader is referred to Bear and Cheng (2010), who offer an overview about the methodology and procedures for constructing conceptual and mathematical models for groundwater flow and the fate and transport of contaminants in both saturated and unsaturated zones. Also, Kuzmin (2010) provides a guide to numerical methods for solving transport equations with particular focus on finite element models.

2.9.2 Boundary and Initial Conditions

In order to obtain a unique solution to a differential equation it is necessary to specify the initial and the boundary conditions that apply. The **initial conditions** describe the values of the variable under consideration, in this case concentration, at some initial time equal to 0. The **boundary conditions** specify the interaction between the area under investigation and its external environment.

There are three types of boundary conditions for mass transport. The boundary condition of the first type is a **fixed concentration.** The boundary condition of the second type is a **fixed gradient. A variable flux** boundary constitutes the boundary condition of the third type.

Boundary and initial conditions are shown in a shorthand form. For one-dimensional flow we need to specify the conditions relative to the location, x, and the time, t. By convention this is shown in the form

$$C(x,t) = C(t)$$

where $C(t)$ is some known function.

For example, we can write

$$\begin{aligned} C(0,t) &= C_0, \quad t \geq 0 \\ C(x,0) &= 0, \quad x \geq 0 \\ C(\infty,t) &= 0, \quad t \geq 0 \end{aligned}$$

The first statement says that for all time t equal to or greater than zero, at $x = 0$ the concentration is maintained at C_0. This is a fixed-concentration boundary condition located at $x = 0$ (first-type boundary). The second statement is an initial condition that says at time $t = 0$, the concentration is zero everywhere within the flow domain, that is, where x is greater than or equal zero. As soon as flow starts, solute at a concentration of C_0 will cross the $x = 0$ boundary.

The third condition shows that the flow system is infinitely long and that no matter how large time gets, the concentration will still be zero at the end of the system (first-type boundary condition at $x = \infty$).

We could also have specified an initial condition that within the domain the initial solute concentration was C_i. This would be written as

$$C(x,0) = C_i, \quad x \geq 0$$

Other examples of concentration (first-type) boundary conditions are exponential decay of the source term and pulse loading at a constant concentration for a period of time followed by another period of time with a different constant concentration.

Exponential decay for the source term can be expressed as

$$C(0,t) = C_0 e^{-it}$$

where i = a decay constant.

Pulse loading where the concentration is C_0 for times from 0 to t_0 and then is 0 for all time more than t_0 is expressed as

$$C(0,t) = C_0 \qquad 0 < t \leq t_0$$

$$C(0,t) = 0 \qquad t > t_0$$

Fixed-gradient boundaries are expressed as

$$\left.\frac{dC}{dx}\right|_{x=0} = f(t) \quad \text{or} \quad \left.\frac{dC}{dx}\right|_{x=\infty} = f(t)$$

where $f(t)$ is some known function. A common fixed-gradient condition is $dC/dx = 0$, or a no-gradient boundary.

The variable-flux boundary, a third type, is given as

$$-D\frac{\partial C}{\partial x} + v_x C = v_x C(t)$$

where $C(t)$ is a known concentration function. A common variable-flux boundary is a constant flux with a constant input concentration, expressed as

$$\left.\left(-D\frac{dC}{dx} + vC\right)\right|_{x=0} = C_0$$

2.9.3 One-Dimensional Step Change in Concentration (First-Type Boundary)

Sand column experiments have been used to evaluate both the coefficients of diffusion and dispersion at the laboratory scale. A tube is filled with sand and then saturated with water. Water is made to flow through the tube at a steady rate, creating, in effect, a permeameter. A solution containing a tracer is then introduced into the sand column in place of the water. The initial concentration of the solute in the column is zero, and the concentration of the tracer solution is C_0. The tracer in the water exiting the tube is analyzed, and the ratio of C, the tracer concentration at time t, over C_0, the injected tracer concentration, is plotted as a function of time. This is called a **fixedstep function.**

The boundary and initial conditions are given by

$$\begin{array}{lll} C(x,0)=0 & x\geq 0 & \text{Initial condition} \\ \left.\begin{array}{ll} C(0,t)=C_0 & t\geq 0 \\ C(\infty,t)=0 & t\geq 0 \end{array}\right\} & & \text{Boundary conditions} \end{array}$$

The solution to Equation 2.18 for these conditions is (Ogata and Banks 1961)

$$C=\frac{C_0}{2}\left[\operatorname{erfc}\left(\frac{L-v_x t}{2\sqrt{D_L t}}\right)+\exp\left(\frac{v_x L}{D_L}\right)\operatorname{erfc}\left(\frac{\mathrm{L}+v_x t}{2\sqrt{D_L t}}\right)\right] \qquad \textbf{(2.21)}$$

This equation may be expressed in dimensionless form as

$$C_R\left(t_R,P_e\right)=0.5\left\{\operatorname{erfc}\left[\left(\frac{P_e}{4t_R}\right)^{1/2}\times(1-t_R)\right]+\exp(P_e)\operatorname{erfc}\left[\left(\frac{P_e}{4t_R}\right)^{1/2}(1+t_R)\right]\right\} \qquad \textbf{(2.22)}$$

where

t_R = $v_x t/L$
C_R = C/C_0
P_e = Peclet number when flow distance, L, is chosen as the reference length ($P_e = v_x L/D_L$)
erfc = complementary error function

Equation 2.21 can be solved in Microsoft Excel after installing the *Plume1D()* add-in (Renshaw 2015a).

2.9.4 One-Dimensional Continuous Injection into a Flow Field (Second-Type Boundary)

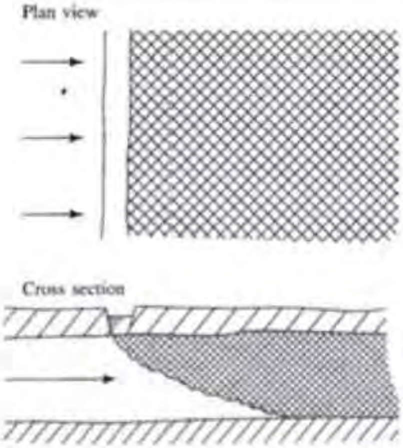
In nature there are not many situations where there would be a sudden change in the quality of the water entering an aquifer. A much more likely condition is that there would be leakage of contaminated water into the groundwater flowing in an aquifer. For the one-dimensional case, this might be a canal that is discharging contaminated water into an aquifer as a line source (Figure 2.14).

The rate of injection is considered to be constant, with the injected mass of the solute proportional to the duration of the injection. The initial concentration of the solute in the aquifer is zero, and the concentration of the solute being injected is C_0. The solute is free to disperse both up-gradient and down-gradient.

The boundary and initial conditions are

$$\begin{array}{lll} C(x,0)=0 & -\infty<x<+\infty & \text{Initial condition} \\ \left.\begin{array}{ll} \int_{-\infty}^{+\infty} n_e C(x,t)\,dx=C_0 n_e v_x t & t>0 \\ C(\infty,t)=0 & t\geq 0 \end{array}\right] & & \text{Boundary conditions} \end{array}$$

FIGURE 2.14 Leakage from a canal as a line source for injection of a contaminant into an aquifer.



Source: J. P. Sauty. 1980. *Water Resources Research* 16:145–58. Copyright by the American Geophysical Union. Reproduced with permission.

The second boundary condition states that the injected mass of contaminant over the domain from $-\infty$ to $+\infty$ is proportional to the length of time of the injection.

The solution to this flow problem (Sauty 1980) is

$$C = \frac{C_0}{2}\left[\operatorname{erfc}\left(\frac{L - v_x t}{2\sqrt{D_L t}}\right) - \exp\left(\frac{v_x L}{D_L}\right)\operatorname{erfc}\left(\frac{L + v_x t}{2\sqrt{D_L t}}\right)\right] \tag{2.23}$$

In dimensionless form this is

$$C_R(t_R, P_e) = 0.5\left\{\operatorname{erfc}\left[\left(\frac{P_e}{4t_R}\right)^{1/2}(1 - t_R)\right] - \exp(P_e)\operatorname{erfc}\left[\left(\frac{P_e}{4t_R}\right)^{1/2}(1 + t_R)\right]\right\} \tag{2.24}$$

It can be seen that Equations 2.21 and 2.23 are very similar, the only difference being that the second term is subtracted rather than added in 2.23.

Sauty (1980) gives an approximation for the one-dimensional dispersion equation as

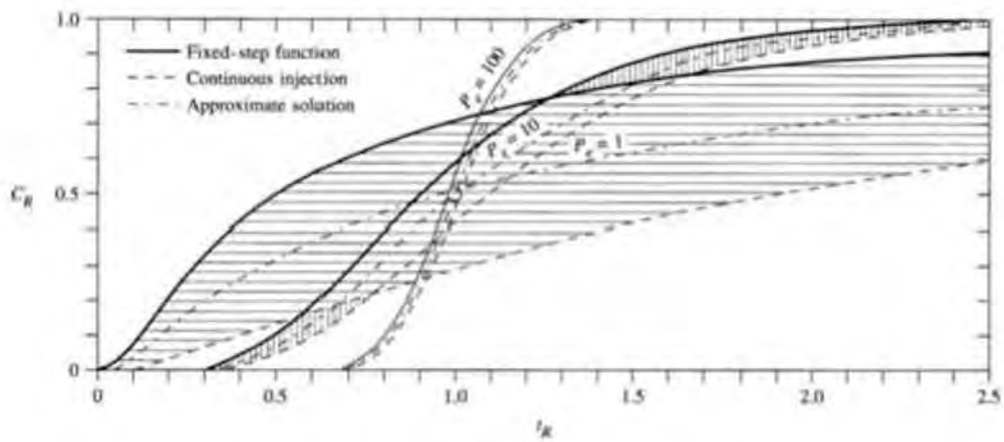
$$C = \frac{C_0}{2}\left[\operatorname{erfc}\left(\frac{L - v_x t}{2\sqrt{D_L t}}\right)\right] \tag{2.25}$$

In dimensionless form this is

$$C_R(t_R, P_e) = 0.5\operatorname{erfc}\left[\left(\frac{P_e}{4t_R}\right)^{1/2}(1 - t_R)\right] \tag{2.26}$$

This approximation comes about because for large Peclet numbers, the second term of Equations 2.21 and 2.23 is much smaller than first term and can be neglected. Figure 2.15 demonstrates under what conditions this approximation is valid. In Figure 2.15 the dimensionless concentration, C_R, is plotted as a function of dimensionless time, t_R, for continuous tracer injection using the fixed-step function, Equation 2.22, the continuous-injection function, Equation 2.24, and the approximate solution, Equation 2.26. Curves are plotted for three Peclet numbers, 1, 10, and 100 (Section 2.7). The Peclet number defines the rate of transport by advection to the rate of transport by hydrodynamic dispersion. For Peclet number 1, the fixedstep function and the continuous-injection function give quite different results, whereas for Peclet number 100 they are almost identical. The approximate solution lies midway between the other two. This figure suggests that for Peclet numbers less than about 10, the exact solutions need to be considered, whereas for Peclet numbers greater than 10, the approximate solution is probably acceptable, especially as the Peclet number approaches 100. This Peclet number increases with flow-path length as advective transport becomes more dominant over dispersive transport. Thus for mass transport near the inlet boundary, it is important to use the correct equation, but as one goes away from the inlet boundary, it is less important that the correct form of the equation is employed.

FIGURE 2.15 Dimensionless-type curves for the continuous injection of a tracer into a one-dimensional flow field.



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EXAMPLE PROBLEM

Pickles are made in large wooden vats. At the Happy Gherkin Pickle Factory one of the vats has been leaking brine directly into the water table. The concentration of chloride in the brine is 1575 mgL^{-1}. The flow in the aquifer that receives the brine is essentially one-dimensional and has the following characteristics.

Hydraulic conductivity = 2.93×10^{-4} ms^{-1}

Hydraulic gradient = 0.00678

Effective porosity = 0.259

The estimated effective diffusion coefficient for chloride is 2×10^{-9} m^{2}s^{-1}.

Calculate the concentration of chloride above any background value at a distance 125 m from the leaking vat 0.50 years after the leak began.

We will apply equation 2.25 to this problem. Note that this is an approximate solution as the second term of equation 2.23 has been dropped.

$$C = \frac{C_0}{2}\left[\operatorname{erfc}\left(\frac{L - v_x t}{2\sqrt{D_L t}}\right)\right]$$

1. Calculate v_x

$$v_x = \frac{K}{n_e}\frac{dh}{dl}$$

$$v_x = \frac{2.93 \times 10^{-4} ms^{-1}}{0.259} \times 0.00678$$

$$v_x = 7.67 \times 10^{-6} ms^{-1}$$

2. Find the value of the coefficient of longitudinal hydrodynamic dispersion, D_L. This can be found from equation 2.11a.

$$D_L = \alpha_L v_x + D^*$$

   a. The first step is to find the value of α_L. This can be estimated from equation 2.48, which will be introduced in a later section.

$$\alpha_L = 0.83(\log L)^{2.414}$$

$$\alpha_L = 0.83(\log 125)^{2.414}\ m$$

$$\alpha_L = 4.96\ \mathrm{m}$$

   b. The next step is to calculate D_L.

$$D_L = 4.96\mathrm{m} \times 7.67 \times 10^{-6}\mathrm{ms}^{-1} + 2 \times 10^{-9}\mathrm{m}^2\mathrm{s}^{-1}$$

$$D_L = 3.80 \times 10^{-5}\mathrm{m}^2\mathrm{s}^{-1} + 2 \times 10^{-9}\mathrm{m}^{2-1}$$

The second term reflecting the effective diffusion coefficient can be neglected as it is so much smaller than the first term.

3. In order to have consistent units, the time must be expressed in seconds.

$$0.5\ \mathrm{y} \times 365\ \mathrm{d/y} \times 1440\ \mathrm{min/d} \times 60\ \mathrm{s/min} = 1.578 \times 10^7\ \mathrm{s}.$$

4. The values of the variables are then substituted into Equation 2.25.

$$C_0 = 1575\ \mathrm{mgL}^{-1}$$

$$v_x = 7.67 \times 10^{-6}\mathrm{ms}^{-1}$$

$$L = 125\mathrm{m}$$

$$D_L = 3.80 \times 10^{-5}\mathrm{m}^2\mathrm{s}^{-1}$$

$$t = 1.578 \times 10^7\mathrm{s}$$

$$C = \frac{1575\text{mgL}^{-1}}{2}\text{erfc}\left(\frac{125\text{m} - (7.67\times10^{-6}\text{ms}^{-1}\times1.578\times10^{7}\text{s})}{2\sqrt{3.80\times10^{-5}\text{m}^{2}\text{s}^{-1}\times1.578\times10^{7}\text{s}}}\right)$$

$$C = 787.5\text{erfc}\left(\frac{125\text{m} - 121.0\text{m}}{2\sqrt{5.99\times10^{2}\text{m}^{2}}}\right)\text{mgL}^{-1}$$

$$C = 787.5\text{erfc}\left(\frac{4.0\text{m}}{2\times24.49\text{m}}\right)\text{mgL}^{-1}$$

$$C = 787.5\text{erfc}(0.0816)\ \text{mg/L}$$

$$C = 787.5\times0.908\text{mgL}^{-1} = 715\text{mgL}^{-1}$$

2.9.5 Third-Type Boundary Condition

A solution for Equation 2.18 for the following boundary condition was given by van Genuchten (1981).

$$C(x,0) = 0 \qquad \text{Initial condition}$$

$$\left.\left(-D\frac{\partial C}{\partial x} + v_x C\right)\right|_{x=0} = v_x C_0 \qquad \text{Boundary conditions}$$

$$\left.\frac{\partial C}{\partial x}\right|_{x\to\infty} = \text{(finite)}$$

The third condition specifies that as x approaches infinity, the concentration gradient will still be finite. Under these conditions the solution to Equation 2.18 is:

$$C = \frac{C_0}{2}\left[\text{erfc}\left[\frac{L - v_x t}{2\sqrt{D_L t}}\right] + \left(\frac{v_x{}^2 t}{\pi D_L}\right)^{1/2}\exp\left[-\frac{(L - v_x t)^2}{4D_L t}\right]\right.$$
$$\left. -\frac{1}{2}\left(1 + \frac{v_x L}{D_L} + \frac{v_x{}^2 t}{D_L}\right)\exp\left(\frac{v_x L}{D_L}\right)\text{erfc}\left[\frac{L - v_x t}{2\sqrt{D_L t}}\right]\right] \tag{2.27}$$

This equation also reduces to the approximate solution, Equation 2.25, as the flow length increases.

2.9.6 One-Dimensional Slug Injection into a Flow Field

If a slug of contamination is instantaneously injected into a uniform, one-dimensional flow field, it will pass through the aquifer as a pulse with a peak concentration, $C_{\max}$, at some time after injection, $t_{\max}$. The solution to Equation 2.18 under these conditions (Sauty 1980) is in dimensionless form:

$$C_R = (t_R, P_e) = \frac{E}{(t_R)^{1/2}}\exp\left(-\frac{P_e}{4t_R}(1 - t_R)^2\right) \tag{2.28}$$

with

$$E = \left(t_{R\max}\right)^{1/2} . \exp\left(\frac{P_e}{4t_{R\max}} \left(1 - t_{R\max}\right)^2 \right) \tag{2.29}$$

where

$t_{R\max}$ = $(1 + P_e^{-2})^{1/2} - P_e^{-1}$ (dimensionless time at which peak concentration occurs)

C_R = $C/C_{\max}$

In Figure 2.16, C_R ($C/C_{\max}$) for a slug injected into a uniform one-dimensional flow field is plotted against dimensionless time, t_R, for several Peclet numbers. It can be seen that the time for the peak concentration ($C_{\max}$) to occur increases with the Peclet number, up to a limit of $t_R = 1$. Breakthrough becomes more symmetric with increasing P_e.

2.9.7 Continuous Injection into a Uniform Two-Dimensional Flow Field

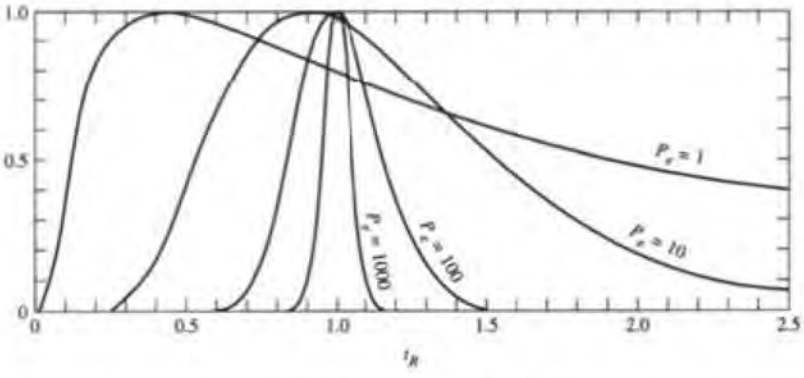
If a tracer is continuously injected into a uniform flow field from a single point that fully penetrates the aquifer, a two-dimensional plume will form that looks similar to Figure 2.16. It will spread along the axis of flow due to longitudinal dispersion and normal to the axis of flow due to transverse dispersion. This is the type of contamination that would spread from the use of an injection well, which would be a point source.

Flow is governed by Equation 2.19, the mass transport equation in two dimensions. The well is located at the origin ($x = 0$, $y = 0$), and there is a uniform flow velocity at a rate v_x parallel to the x axis. There is a continuous injection at the origin, of a solute with a concentration C_0 at a rate Q over the aquifer thickness, b.

The solution of Equation 2.19 can be found from a Green function (Bear 1972; Fried 1975) for the injection of a unit amount of a contaminant as:

$$C(x,y,t) = \frac{1}{4\pi t\left(D_L D_T\right)^{0.5}} \exp\left[-\frac{\left(x - v_x t\right)^2}{4D_L t} - \frac{y^2}{4D_T t} \right]$$

FIGURE 2.16 Dimensionless-type curve for the injection of a slug of a tracer into a one-dimensional flow field.



Source: J. P. Sauty. 1980. *Water Resources Research* 16:145–158. Copyright by the American Geophysical Union. Reproduced with permission.

Since the Green function is for a unit injection, and we have an injection rate that can be defined as $C_0(Q/b)$, the solution to the above is:

$$C(x,y,t) = \frac{C_0(Q/b)dt}{4\pi t\left(D_L D_T\right)^{0.5}} \exp\left[-\frac{\left(x - v_x t\right)^2}{4D_L t} - \frac{y^2}{4D_T t}\right]$$

If the injection rate, Q/b, is continuous then the solution at time t is:

FIGURE 2.17 Plume resulting from the continuous injection of a tracer into a two-dimensional flow field. (Source: C. W. Fetter. 1994. *Applied Hydrogeology, Third Edition*. Upper Saddle River, New Jersey: Prentice-Hall, Inc.)

$$C(x,y,t) = \frac{C_0(Q/b)}{4\pi\left(D_L D_T\right)^{0.5}} \int_{\theta=0}^{\theta=t} \exp\left[-\frac{\left(x - v_x\theta\right)^2}{4D_L\theta} - \frac{y^2}{4D_T\theta}\right]\frac{d\theta}{\theta} \qquad \textbf{(2.30)}$$

Steady-state conditions are obtained when time approaches infinity. Therefore equation 2.30 is integrated from 0 to ∞. The result is:

$$C(x,y) = \frac{C_0(Q/b)}{2\pi\left(D_L D_T\right)^{1/2}} \exp\left(\frac{v_x x}{2D_L}\right) K_0\left[\left(\frac{{v_x}^2}{4D_L}\left(\frac{x^2}{D_L} + \frac{y^2}{D_T}\right)\right)^{1/2}\right] \qquad \textbf{(2.30a)}$$

where

K_0 = the modified Bessell function of the second kind and zero order (values are tabulated in Appendix B)
Q = the rate that the contaminant is injected
b = the thickness of the aquifer over which the contaminant is injected

Equation 2.30a can be solved in EXCEL after installing the Plume2DSS() add-in (Renshaw 2015b).

EXAMPLE PROBLEM

A waste liquid containing fluoride at a concentration of 133 mg/L was pumped into a shallow disposal pit located above a thin, 1.75 m thick, (two-dimensional) aquifer at a rate of 3.66 m^3/day for many years. The average linear velocity of the groundwater was 0.187 m/day. Assume that the transverse dispersion is 10% of the longitudinal dispersion. If the disposal pit is assumed to be at a location of $x_0 = 0$ and $y_0 = 0$, what would the concentration of fluoride be in a monitoring well located at $x = 123$ m and $y = 16$ m? Assume that the fluoride is non-reactive and non-adsorbed by the aquifer.

1. First the value of α_L must be calculated using equation 2.48.

   $\alpha = 0.83(\log(L))^{2.414}$

   L is equal to $x - x_0$ or 123 m.

   $\alpha_L = 0.83(\log(123))^{2.414}$

   $\alpha_L = 4.919$ m

2. Next the value of D_L and D_T must be found.

   $$D_L = v_x \alpha_L$$

   $$D_L = 0.187 \text{ m/da} \times 4.919 \text{ m} = 0.920 \text{ m}^2/\text{da}$$

   $$D_T = 0.10\ D_L$$

   $$D_T = 0.092 \text{ m}^2/\text{da}$$

   The variables are then inserted into equation 2.30a.

   $C_0 = 133$ mg/L

   $Q = 3.66 \text{ m}^3/\text{da}$

   $b = 1.75$ m

$$C = \frac{C_0(Q/b)}{2\pi(D_L D_T)^{1/2}} \exp\left(\frac{v_x x}{2D_L}\right) K_0\left[\left(\frac{v_x{}^2}{4D_L}\left(\frac{x^2}{D_L} - \frac{y^2}{D_T}\right)\right)^{1/2}\right]$$

$$C = \frac{133\text{mg/L} \times (3.66\text{m}^3/\text{da}/1.75\text{m})}{2 \times \pi \times (0.92\text{m}^2/\text{da} \times 0.092\text{m}^2/\text{da})^{1/2}} \times \exp\left(\frac{0.187\text{m/da} \times 123\text{m}}{2 \times 0.92\text{m}^2/\text{da}}\right)$$

$$K_0\left[\left(\frac{0.187^2\text{m}^2/\text{da}^2}{4 \times 0.92\text{m}^2/\text{da}}\left(\frac{123^2\text{m}^2}{0.92\text{m}^2/\text{da}} + \frac{16^2\text{m}^2}{0.092\text{m}^2/\text{da}}\right)\right)^{1/2}\right]$$

$$C = \frac{278.0\text{mg/L}}{1.828} \exp\left(\frac{23.0}{1.84}\right) K_0\left[[0.0095 \times (16445 + 2783)]^{1/2}\right]$$

$$C = 152.1\exp(12.5) K_0(13.52)\text{mg/L}$$

$$C = 152.1 \times 268337 \times 4.544 \times 10^{-7}\text{mg/L}$$

Note: Although K_0, a modified Bessell function of the zero order and second kind, can be obtained from Appendix B for a limited range of values, the table did not contain K_0 of 13.52. The value listed above, 4.54×10^{-7} was generated by a EXCEL function BESSELK(x,n).

According to Equation 2.30, as the value of D_L approaches zero, the concentration will approach infinity. As this is a physical impossibility, if the value of D_L is very small, then the one-dimensional equation, 2.23, should be used with a large value for time.

Equation 2.30 can also be solved for a specific value of time, so that the spread of a two-dimensional plume with time can be determined. In order to solve for time, Equation 2.30 can be written thusly:

$$C(x,y,t)=\frac{C_0(Q/b)}{4\pi(D_LD_T)^{1/2}}\exp\left(\frac{v_x x}{2D_L}\right)\int_{\theta=0}^{\theta=t}\exp\left[-\frac{\theta}{4D_L}-\left(\frac{x^2}{4D_L}+\frac{y^2}{4D_T}\right)\frac{1}{\theta}\right]\frac{d\theta}{\theta}$$

If we set $t_D = v_x^2/4\,D_L$, then the above becomes:

$$C(x,y,t)=\frac{C_0(Q/b)}{4\pi(D_LD_T)^{1/2}}\exp\left(\frac{v_x x}{2D_L}\right)\int_{t_{D=0}}^{t_{D=t}}\exp\left[-t_D-\frac{B^2}{4t_D}\right]\frac{dt_D}{t_D}$$

with

$$B^2=\frac{{v_x}^2x^2}{4{D_L}^2}+\frac{{v_x}^2y^2}{4D_LD_T}$$

The integral in the above equation was solved by Hantush (1956). This solution is

$$C(x,y,t)=\frac{C_0(Q/b)}{4\pi\left(D_LD_T\right)^{1/2}}\exp\left(\frac{v_x x}{2D_L}\right)\left[W(0,B)-W(t_D,B)\right] \qquad \textbf{(2.31)}$$

with t_D and B as defined above.

It should be noted that in effect t_D is a dimensionless form of time. The values of $W[t_D, B]$ can be found in Hantush (1956) and a limited series is tabulated in Appendix C. It can also be determined in EXCEL after installing the Leaky() add-in (Renshaw 2015c). In well hydraulics this is known as the leaky well function, $W[u, r/b]$.

EXAMPLE PROBLEM

An underground tank which formerly held benzene but now holds water is leaking at a rate of 1.93m³/year. However, the water still contains some benzene at a concentration of 12,950 µg/L. The groundwater which flows beneath the leaking tank goes directly north. A drinking water supply well is located at a spot that can be located by going 123.5m due north of the leaking tank and then 7.2m due east. Assume that the average linear velocity of the groundwater is 0.235 m/day and the longitudinal dispersivity is 12m and the lateral dispersivity is 1.2m and the aquifer thickness is 1.00m. What would the benzene concentration be after 2.00 years?

This is an example of a continuous leakage into a two dimensional flow field; equation 2-31.

1. The values of D_L and D_T must be calculated from equations 2-11a and 2-11b. We will ignore the effective diffusion coefficient as it is so much smaller than dispersivity.

$$D_L=\alpha_L v_X=12\text{ m}\times 0.235\text{ m/day}=2.82\text{ m}^2\text{/day}$$

$$D_T=\alpha_T v_X=1.2\text{ m}\times 0.235\text{ m/day}=0.282\text{ m}^2\text{/day}$$

2. The value of B must be calculated.

$$B = \left[\frac{(v_x x)^2}{4D_L{}^2} + \frac{(v_x y)^2}{4D_L D_T}\right]^{\frac{1}{2}}$$

$$B = \left[\frac{(0.235\text{m}/\text{da} \times 123.5\text{m})^2}{4 \times (2.8\text{m}^2/\text{da})^2} + \frac{(0.235/\text{da} \times 7.2\text{m})^2}{4 \times 2.8\text{m}^2/\text{da} \times 0.28\text{m}^2/\text{da}}\right]^{\frac{1}{2}}$$

$$B = \left[\frac{842\text{m}^4/\text{da}^2}{31.4\text{m}^4/\text{da}^2} + \frac{2.86\text{m}^4/\text{da}^2}{3.14\text{m}^4/\text{da}^2}\right]^{\frac{1}{2}}$$

$$B = \sqrt{26.8 + 0.91}$$

$$B = 5.26$$

3. The next step is to find t_D, Convert time in years to time in days by multiplying by 365 days per year.

$$t_D = \frac{v_x{}^2 t}{4D_L}$$

$$t_D = \frac{(0.235\text{m}/\text{da})^2 \times 730\text{da}}{4 \times 2.82\text{m}^2/\text{da}}$$

$$t_D = 3.57$$

4. One must now find W[0, B] and W[t_D, B] from Appendix C.

   W[0, B] = W[0, 5.26] = 0.0098

   W[t_D, B] = W[3.57, 5.26] = 0.0019

5. The values are then substituted into Equation 2.31. The rate of leakage, Q, is converted into cubic meters per day by dividing by 365. The aquifer thickness is 1.00m.

   $Q = 1.93\ \text{m}^3/\text{year}/365\ \text{da}/\text{year} = 0.0053\ \text{m}^3/\text{da}$

$$C(x,y,t) = \frac{C_0 Q/b}{4\pi(D_L D_T)^{1/2}} \exp\left(\frac{v_x x}{2D_L}\right)\left[W(0,B) - W(t_D,B)\right]$$

$$C(x,y,t) = \frac{12{,}950\mu\text{g}/\text{L} \times 0.0053\text{m}^3/\text{da}/1\text{m}}{4\pi(2.82\text{m}^2/\text{da} \times 0.28\text{m}^2/\text{da})^{1/2}} \exp\left(\frac{0.236\text{m}/\text{da} \times 123.5\text{m}}{2 \times 2.82\text{m}^2/\text{da}}\right)[0.0098 - 0.0019]$$

$$C(x,y,t) = 0.0061\ \exp(5.16)[0.0079]\mu\text{g}/\text{L}$$

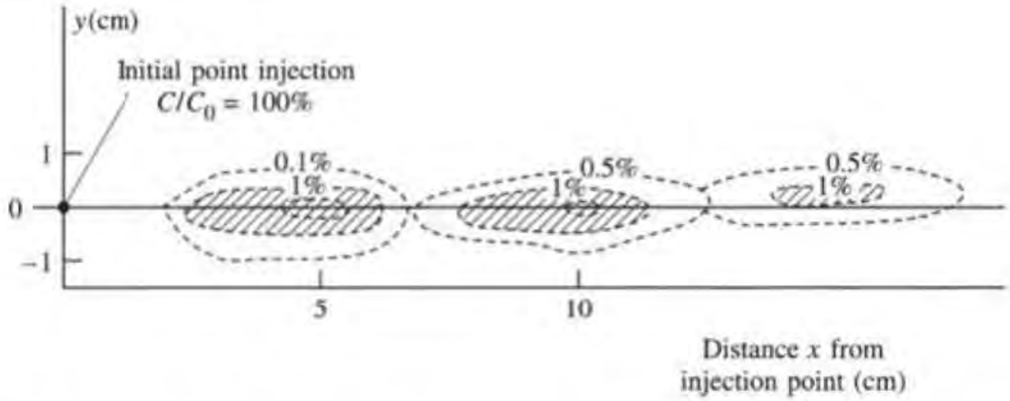
$$C(x,y,t) = 0.0061 \times 174 \times 0.0079\mu\text{g}/\text{L}$$

$$C(x,y,t) = 0.0084\mu\text{g}/\text{L}$$

2.9.8 Slug Injection into a Uniform Two-Dimensional Flow Field

If a slug of contamination is injected over the full thickness of a two-dimensional uniform flow field in a short period of time, it will move in the direction of flow and spread with time. This result is illustrated by Figure 2.18 and represents the pattern of contamination at three increments that result from a one-time spill. Figure 2.18 is based on the results of a laboratory experiment conducted by Bear (1961). Figure 2.19 shows the spread of a plume of chloride that was injected into an aquifer as a part of a large-scale field test (Mackay et al. 1986). The plume that resulted from the field test is more complex than the laboratory plume due to the heterogeneities encountered in the real world and the fact the plume may not be following the diffusional model of dispersion.

FIGURE 2.18 Injection of a slug of a tracer into a two-dimensional flow field shown at three time increments.



Experimental results from J. Bear, 1961. *Journal of Geophysical Research* 66:2455–2467. Copyright by the American Geophysical Union. Reproduced with permission.

De Josselin and De Jong (1958) derived a solution to this problem on the basis of a statistical treatment of lateral and transverse dispersivities. Bear (1961) later verified it experimentally. If a tracer with concentration C_0 is injected into a two-dimensional flow field over an area A at a point (x_0, y_0), the concentration at a point (x, y), at time t after the injection is

$$C(x,y,t) = \frac{C_0 A}{4\pi t (D_L D_T)^{1/2}} \exp\left[-\frac{((x-x_0)-v_x t)^2}{4D_L t} - \frac{(y-y_0)^2}{4D_T t} \right] \tag{2.32}$$

EXAMPLE PROBLEM

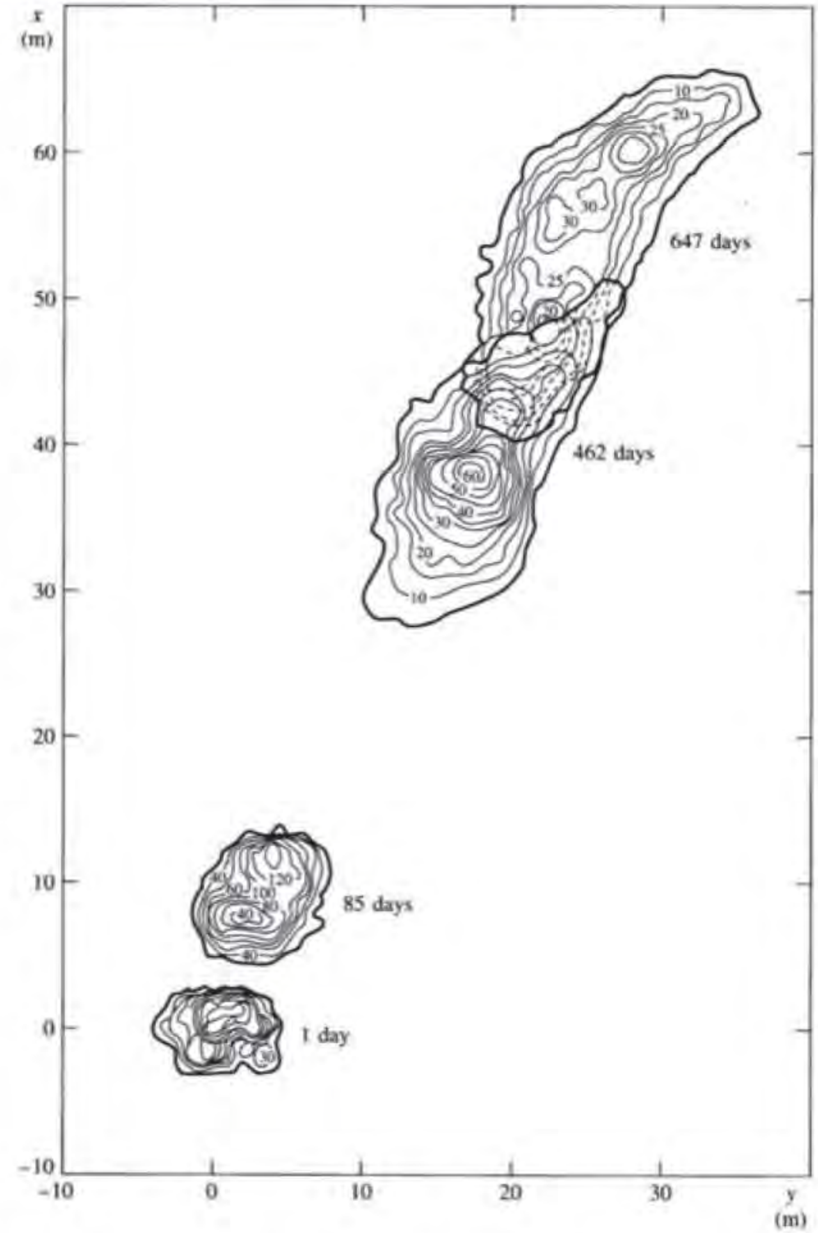
A tank truck, which is carrying water containing 1275 mg/L of dissolved benzene overturns and spills a volume of water sufficient to saturate a thin aquifer over an area of 5 m². The aquifer contains groundwater flowing with an average linear velocity of 0.45 m/day. Assume that the values of D_L and of D_T are 2.1 m²/day and 0.21 m²/day respectively.

There is a nearby private well at a seasonal cottage. If the center of the spill is at location $x_0 = 0$ and $y_0 = 0$, then the location of the well is $x = 72$ m and $y = 5.5$ m. The owners of the private well are away for the season and will not return for another 200 days.

If there is no degradation or retardation of the benzene as it moves through the aquifer, what will the concentration of benzene be in the private well when the owner returns.

The correct equation to use is 2.32 for a slug injection of contamination into a two dimensional aquifer.

FIGURE 2.19 Vertically averaged chloride concentration at 1 day, 85 days, 462 days, and 647 days after the injection of a slug into a shallow aquifer.



Source: D. M. Mackay et al. 1986. *Water Resources Research* 22:2017–2029. Copyright by the American Geophysical Union. Reproduced with permission.

$$C = \frac{C_0 A}{4\pi t\sqrt{D_L D_T}} \exp\left[-\frac{((x - x_0) - v_x t)^2}{4D_L t} - \frac{(y - y_0)^2}{4D_T t} \right]$$

$$C = \frac{1275\text{mgL}^{-1} \times 5\text{m}^2}{4 \times \pi \times 200\text{da} \times \sqrt{2.1\text{m}^2\text{da}^{-1} \times 0.21\text{m}^2\text{da}^{-1}}} \times$$

$$\exp\left[-\frac{((72\text{m} - 0) - (0.45\text{mda}^{-1} \times 200\text{da}))^2}{4 \times 2.1\text{md}^{-1} \times 200\text{da}} - \frac{(5.5\text{m})^2}{4 \times 0.21\text{m}^2\text{da}^{-1} \times 200\text{da}}\right]$$

$$C = \frac{6375\text{mgL}^{-1} \times \text{m}^2}{4 \times \pi \times 200\text{da} \times 0.664\text{m}^2\text{da}^{-1}} \exp[-\frac{(72-90)^2\text{m}^2}{1680\text{m}^2} - \frac{30.25\text{m}^2}{168\text{m}^2}]$$

$$C = 3.82\text{mgL}^{-1}\exp[-0.192 - 0.180]$$

$$C = 3.82\exp(-0.372) = 3.82 \times 0.6892 = 2.63\text{mgL}^{-1}$$

The maximum concentration of a contaminant from a slug injection is found in the center of the plume, or the *center of mass.* If the flow is in the direction of the x axis, and the spill was at location $x_0 = 0$ and $y_0 = 0$, the center of mass of a conservative substance at any time t since the spill will be at a location where $x = v_x t$ and $y = 0$. If we substitute these values into equation 2–32, we obtain:

$$C_{max} = \frac{C_0 A}{4t\pi\sqrt{D_T D_L}} \exp\left[-\frac{((v_x t - 0) - v_x t))^2}{4D_L t} - \frac{(0-0)^2}{4D_T t}\right]$$

$$C_{max} = \frac{C_0 A}{4t\pi\sqrt{D_T D_L}} \exp(0)$$

$$C_{max} = \frac{C_0 A}{4t\pi\sqrt{D_T D_L}} \qquad \textbf{(2.32a)}$$

The distribution of contamination in the plume will follow a normal or Gaussian distribution. From equations 2-12a and 2-12b the standard deviation of the distribution is given by:

$$\sigma_x = \sqrt{2D_L t} \qquad\qquad \sigma_y = \sqrt{2D_T t}$$

By definition, 99.7% of the mass of contamination will be contained within an area represented by three standard deviations away from the center of mass of the plume. Thus the plume can be defined by the location of the center of mass, $3\sigma_x$ and $3\sigma_y$.

EXAMPLE PROBLEM

A truck carrying dilute brine with 2130 mg/L chloride from the cleanup of a pond containing waste from a producing oil well overturns and spills the dilute brine over an area of 455 square feet. The underlying thin aquifer has an average linear groundwater velocity of 1.23 ft/day. Where would the center of mass of the plume be in

133 days, what would the maximum concentration be and how far beyond and to the side of the center of mass would the plume spread?

1. The plume would be advected by the flowing groundwater so that the center of mass would be at $x = v_x t$.

   $x = 1.23$ ft/da × 133 da = 164 feet.

2. The maximum concentration at the center of mass can be found from equation 2.32a.

   $$C_{max} = \frac{C_0 A}{4t\pi\sqrt{D_T D_L}}$$

   a. We need to find the values of D_L and D_T. This can be done using equations 2.11a and 2.11b; but, first we need to use equation 2.82 to estimate α_L

   $$\alpha_L = 0.83(\log(L))^{2.414}$$
   $$= 5.66 \text{ ft}$$
   $$D_L = \alpha_L v_x$$
   $$= 5.66 \text{ ft x } 1.23 \text{ ftda}^{-1}$$
   $$= 6.96 \text{ ft}^2\text{da}^{-1}$$

   We can assume D_T to be 10% of D_L

   $D_T = 0.696 \text{ ft}^2\text{da}^{-1}$

   The appropriate variables are substituted into equation 2.32.

   $$C_{max} = \frac{2130 \; mgL^{-1} \times 455 \; ft^2}{4 \times \pi \times 133da\sqrt{6.96 \; ft^2da^{-1} \times 0.696 \; ft^2da^{-1}}}$$

   $$C_{max} = 263 \; mgL^{-1}$$

3. The size of the plume can be determined from the standard deviations.

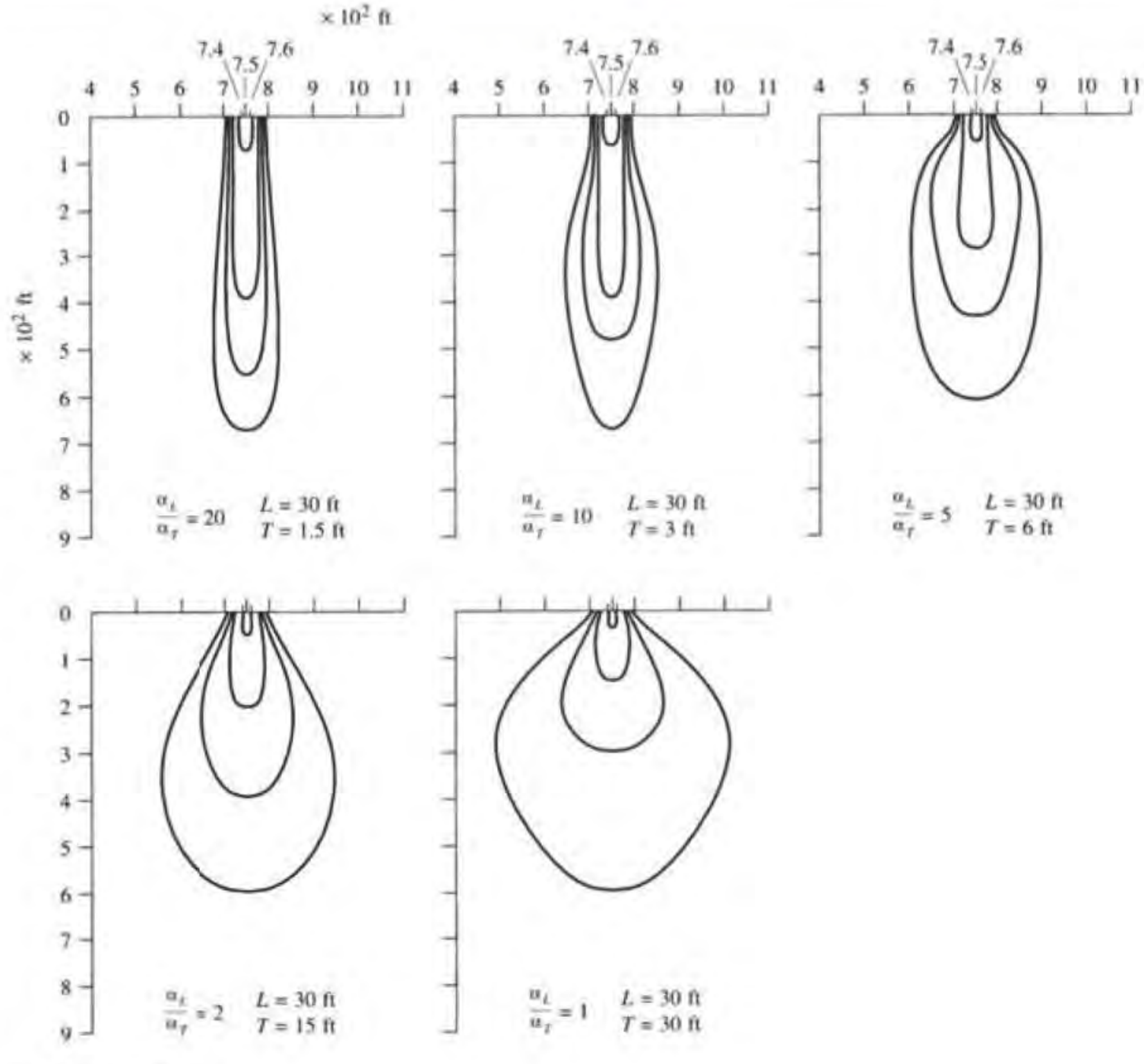
$$\sigma_x = \sqrt{2D_L t} \qquad \sigma_y = \sqrt{2D_T t}$$
$$\sigma_x = \sqrt{2 \times 6.96 \text{ ft}^2\text{da}^{-1} \times 133 \text{ da}} \qquad \sigma_y = \sqrt{2 \times 6.96 \text{ ft}^2\text{da}^{-1} \times 133 \text{ da}}$$
$$\sigma_x = 43.0 \text{ ft} \qquad \sigma_y = 13.6 \text{ ft}$$

The leading edge of the plume is $3\sigma_x$ feet ahead of the center of mass or 129 feet and the plume had spread out $3\sigma_y$ feet on either side of the center of the mass or 40.8 feet.

■ 2.10 Effects of Transverse Dispersion

The ratio of longitudinal to transverse dispersivity (α_L/α_T) in an aquifer is an important control over the shape of a contaminant plume in two-dimensional mass transport. The lower the ratio, the broader the shape of the resulting plume will be. Figure 2.20 shows various two-dimensional shapes of a contaminant plume, where the only factor varied was the ratio of longitudinal to transverse dispersivity. This illustrates the fact that it is important to have some knowledge of the transverse dispersivity in addition to the longitudinal dispersivity. There is a paucity of data in the literature on the relationships of longitudinal to transverse dispersivities. From the few field studies available, α_L/α_T is in the range of 6 to 20 (Anderson 1979; Klotz et al. 1980). In addition, dispersivity ratios based on field studies are based on fitting the diffusional model of dispersion to cases where it might not be applicable.

FIGURE 2.20 The effect of changing dispersivity ratio on the spread of a contaminant plume from a continuous source.



Source: Robert L. Stollar

chloride was 48 mgL^{-1} and after 4000 seconds, t_2, it was 252 mgL^{-1}. What is the dispersivity of the sand in the soil column?

The number of pore volumes at a given time can be calculated from Equation 2.33:

$$PV = v_x t / L$$

For the first measurement at t_1:

$$PV = 1.35 \times 10^{-2}\ \mathrm{cms}^{-1}\ 500\ \mathrm{s}/40\ \mathrm{cm} = 0.17\ \text{pore volumes}$$

For the second measurement at t_2:

$$PV = 1.35 \times 10^{-2}\ \mathrm{cms}^{-1} \times 4000\ \mathrm{s}/40\ \mathrm{cm} = 1.35\ \text{pore volumes}$$

At t_1, C/C_0 is 48/300, which equals 0.16. With a pore volume of 0.17

$$(PV - 1)/PV^{1/2} = (0.17 - 1)/(0.17)^{1/2} = -2.01$$

At t_2, C/C_0 is 252/300, which equals 0.84. With a pore volume of 1.32

$$(PV - 1)/PV^{1/2} = (1.32 - 1)/(1.32)^{1/2} = 0.28$$

Since C/C_0 at t_1 is conveniently equal to 0.16, then $(PV - 1)/PV^{1/2}$ for t_1 turns out to be $J_{0.16}$ Likewise C/C_0 at t_2 is 0.84 so that $(PV - 1)/PV^{1/2}$ for t_2 is $J_{0.84}$.

The value of D_L can be found from Equation 2.35:

$$D_L = \left(\frac{v_x L}{8}\right)(J_{0.84} - J_{0.16})^{1/2}$$

$$D_L = (1/8) \times (1.35 \times 10^{-2}\ \mathrm{cms}^{-1} \times 40\ \mathrm{cm}) \times (0.28 - -2.01)^{1/2}$$

$$= 6.75 \times 10^{-2} \times 1.51\mathrm{cm}^2\mathrm{s}^{-1}$$

$$= 0.102\ \mathrm{cm}^2\mathrm{s}^{-1}$$

2.11.2 Quantifying Dispersivity in the Field

A value for dispersivity can be determined in the field by two means. If there is a contaminated aquifer, the plume of known contamination can be mapped and the advection-dispersion equation solved with dispersivity as the unknown. Pinder (1973) used this approach in a groundwater modeling study of a plume of dissolved chromium in a sand and gravel aquifer on Long Island, New York. He started with initial guesses of α_L and α_T and then varied them during successive model runs until the computer model yielded a reasonable reproduction of the observed contaminant plume. One of the difficulties of this approach is that the concentration and volume of the contaminant source are often not known.

A much more common approach is the use of a tracer that is injected into the ground via a well. There are a variety of variations to this approach. **Natural gradient tests** involve the injection of a tracer into an aquifer, followed by the measurement of the plume that developed under the prevailing water table gradient (e.g., Sudicky and Cherry 1979;

Gillham et al. 1984; Mackay et al. 1986; LeBlanc et al. 1991; Garabedian et al. 1991; Olsen and Tenbus 2004). The plume is measured by means of small amounts of water withdrawn from down-gradient observation wells and multilevel piezometers. Many of these field tests showed that thin plumes with less than expected transverse dispersivity often occur in field situations. This underlines a growing acceptance of the need for high resolution, vertically discrete, multilevel aquifer monitoring. Multilevel monitoring will be discussed in Chapter 8. One and two-well tests have also been used in which a tracer is pumped into the ground and then groundwater containing the tracer is pumped back out of the ground (e.g., Fried 1975; Grove and Beetem 1971; Sauty 1978; Pickens et al 1981; Pickens and Grisak, 1981). These so-called **forced hydraulic gradient tests** have the advantage that they can be completed in much shorter time relative to natural gradient tests. However, these tests require treatment if the pumped groundwater is contaminated. Also, the results of forced hydraulic gradient tests do not truly reflect the natural groundwater flow conditions. Ptak et al. (2004) reviewed the advantages and disadvantages of natural or forced hydraulic gradient tests for both nonreactive and reactive tracer compounds can be used.

2.11.3 Single-Well Tracer Test

A single-well tracer test involves the injection of water containing a conservative tracer into an aquifer via an injection well and then the subsequent pumping of that well to recover the injected fluid. The fluid velocities of the water being pumped and injected are much greater than the natural groundwater gradients.

Equation 2.20 can be written (Hoopes and Harleman 1967) as

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial r} = \alpha_L u \frac{\partial^2 C}{\partial r^2} + \frac{D^*}{r}\frac{\partial}{\partial r}\left(r\frac{\partial C}{\partial r}\right) \tag{2.37}$$

Gelhar and Collins (1971) derived a solution to Equation 2.37 for the withdrawal phase of an injection-withdrawal well test in which the diffusion term is neglected because it is very much smaller than the dispersion term. The relative concentration of the water being withdrawn from the injection well is

$$\frac{C}{C_0} = \frac{1}{2}\operatorname{erfc}\left(\frac{(U_p - U_i) - 1}{\{\frac{16}{3}(\alpha_L / R_f)[2-(1-U_p/U_i)]^{1/2}[1-(U_p/U_i)]\}^{1/2}}\right) \tag{2.38}$$

where

U_p = cumulative volume of water withdrawn during various times

U_i = total volume of water injected during the injection phase

R_f = average frontal position of the injected water at the end of the injection period, which is defined by

$$R_f = \left(\frac{Qt}{\pi bn}\right)^{1/2} \tag{2.39}$$

where

Q = rate of injection

t = total time of injection

b = aquifer thickness

n = porosity

EXAMPLE PROBLEM

Pickens and Grisak (1981) performed a single-well injection-withdrawal tracer test into a confined sand aquifer about 8.2 m thick with an average hydraulic conductivity of 1.4×10^{-2} cm/sec and a porosity of 0.38. The sediment tested in the column study described in the dispersivity example problem above came from this aquifer.

The injection well was 5.7 cm in diameter and the full thickness of the aquifer was screened. Clear water was injected at a constant rate for 24 hr prior to the start of the test to establish steady-state conditions. The tracer used during the tests was ^{131}I, a radioactive iodine isotope, which was added to the injected water. All measurements were corrected for the radioactive decay that occurred during the test.

Two tests were performed on the well. The first test, SWI, had an injection rate of 0.886 L/sec and injection continued for 1.25 da. A total volume of 95.6 m^3 of water was injected, and the injection front reached an average radial distance away from the well of 3.13 m. Water was then pumped for 2.0 da at the same rate, so that a total of 153 m^3 of water was withdrawn. The second test, SW2, was longer. Water with the tracer was added at a rate of 0.719 L/sec for 3.93 da. A total of 244 m^3 of water was added, and the average position of the injection front reached to 4.99 m from the well. During the withdrawal phase a total of 886 m^3 of water was pumped over a period of 16.9 da at an average rate of 0.606 L/sec.

The results of the test are shown in Figure 2.22. Relative concentration, C/C_o, is plotted against U_p / U_r. The dots represent field values and the solid lines are curves, which were computed using Equation 2.38. Various curves were computed for different values of α_L, and the curves with the best fit to the field data were plotted on the graphs. In Figure 2.22(a) the calculated curve was based on a longitudinal dispersivity of 3.0 cm, whereas for curve 2.22(b) the best-fit curve was based on a longitudinal dispersivity of 9.0 cm. This test illustrates the scale-dependent nature of dispersion. The second test, in which a larger volume of water was injected, tested a larger volume of the aquifer than the first test and yielded a higher dispersivity value.

■ 2.12 Scale Effect of Dispersion

The two example problems derived from Pickens and Grisak (1981) illustrate what has been called the **scale effect of dispersion** (Fried 1975). At the laboratory scale the mean value of α_L was determined to be 0.035 cm (0.014 in) when the flow length was 30 cm (12 in). With the single-well injection-withdrawal test, α_L was 3 cm (1.2 in) when the solute front traveled 3.1 m (10.2 ft) and 9 cm (3.5 in) when the solute front traveled 5.0 m (16.4 ft). In a two-well recirculating withdrawal-injection tracer test with wells located 8 m (26.2 ft) apart α_L was determined to be 50 cm (19.6 in). All these values were obtained from the same site. The greater the flow length, the larger the value of longitudinal dispersivity needed to fit the data to the advection-dispersion equation.

spread. In this region the variance of the plume will grow proportionally to the time or mean travel distance, as it does at the laboratory column scale. The advective-dispersion model is based on the assumption that dispersion follows Fick's law. Some authors contend that dispersion follows Fick's law only at the laboratory scale, where it is caused by local mechanical dispersion, and for very long flow paths, where the effects of advection through heterogeneous materials and local transverse dispersion create macroscale dispersion that follows Fick's law (e.g., Gelhar 1986; Dagan 1988). The contention that macroscale dispersion becomes Fickian (i.e., follows Fick's law) at long travel times and distances is somewhat controversial, especially if the flow is through geological formations that are heterogeneous at different scales (Anderson 1990).

2.13 Stochastic Models of Solute Transport

2.13.1 Introduction

The normal manner of determining a field-scale dispersion coefficient is to look for a natural tracer or inject a tracer into an aquifer and observe the resulting development of a plume. A solute-transport model is then constructed and the computed solute distribution is fitted to the observed field data by adjusting the dispersion coefficients. Dispersion coefficients obtained in this manner are fitted curve parameters and do not represent an intrinsic property of the aquifer. This is especially true when the aquifer is assumed to be homogeneous and is described by a single value for hydraulic conductivity and porosity. It is apparent that flow and transport modeling based on a single value for porosity and hydraulic conductivity is a gross simplification of the complexity of nature. For analytical solutions, we are constrained to use of a single value for average linear velocity, and for numerical models we often use a single value because that is all we have.

A **deterministic model** is one where a partial differential equation is solved, either numerically or analytically, for a given set of input values, aquifer parameters, and boundary conditions. The resulting output variable has a specific value at a given place in the aquifer. It is assumed that the distribution of aquifer parameters is known. The equations given earlier in this chapter are examples of deterministic models.

A **stochastic model** is a model in which there is a statistical uncertainty in the value of the output variables, such as solute distribution. The probabilistic nature of this outcome is due to the fact that there is uncertainty in the value and distribution of the underlying aquifer parameters, such as the distribution and value of hydraulic conductivity and porosity (Freeze 1975; Dagan 1988).

A widespread misconception about stochastic and deterministic models is that the latter use physical laws, while the stochastic models are largely empirical and based entirely on statistical data-analysis. In reality, any physically-based model becomes a stochastic model once its inputs, parameters, or outputs are treated as random (Bierkens and van Geer; 2014).

The idea behind stochastic modeling is very attractive. It is obvious that it takes a great effort to determine hydraulic conductivity and porosity at more than a few locations in an aquifer system. If we could determine the distribution of aquifer properties with a high degree of detail, then a numerical solution of a deterministic model would yield results with a high degree of reliability. However, with limited knowledge of aquifer parameters, a deterministic model makes only a prediction of the value of an output variable at a given point and time in the aquifer. The stochastic model is based on a probabilistic distribution of aquifer parameters. At the outset it is recognized in the stochastic model that the result will be only some range of possible outcomes. The stochastic model thus recognizes the probabilistic nature of the answer, whereas the deterministic model suggests that there is only one "correct" answer. Of course, the experienced hydrogeologist recognizes the uncertainty even in the deterministic answer. There have been literally hundreds of papers written on various aspects of stochastic modeling of groundwater flow and solute transport. Textbooks like Zhang (2001), Rubin (2003), and Dagan and Neuman (2005) provide insights into analyzing and modeling subsurface heterogeneity using stochastics concepts and models for managing water resources, preserving subsurface water quality, storing energy and wastes, besides other applications.

2.13.2 Stochastic Descriptions of Heterogeneity

Stochastic hydrology is about combining deterministic model outcomes with a probability distribution of the errors, or alternatively, considering the hydrological variable as random and determining its probability distribution and some "best prediction" (Bierkens and van Geer 2014). The greatest uncertainty in the input parameters of a model is the value of hydraulic conductivity, because it varies over such a wide range for geologic materials. If we make a measurement of hydraulic conductivity at a given location, the only uncertainty in its value at that location is due to errors in measuring its value. However, at all locations where hydraulic conductivity is not measured, additional uncertainty exists. If we make a number of measurements of the value of hydraulic conductivity, we can estimate this uncertainty using certain statistical techniques.

Let us define Y as the log of the hydraulic conductivity, K, and assume that the log value Y is normally distributed. We will assume a one-dimensional series of Y values $\{Y_1, Y_2, Y_3, Y_4, \ldots Y_n\}$ (Freeze et al. 1990). Therefore,

$$Y_i = \log K_i \tag{2.40}$$

The population that consists of all of the values of Y has a mean value, μ_y, and a standard deviation, σ_y. The only way to obtain precise values of μ_y and σ_y would be to sample the aquifer everywhere, clearly an impossible task, but we can find estimates of their values based on the locations where we have actually measured K. If we have a series of Y values $\{Y_1, Y_2, Y_3, \ldots Y_n\}$, as in Figure 2.27(a), based on measured value of K, then our estimate of the population mean is obtained from the mean value of the sampled values, Y, which can be found from

$$\overline{Y} = \frac{1}{n}\sum_{i=1}^{n} Y_i \tag{2.41}$$

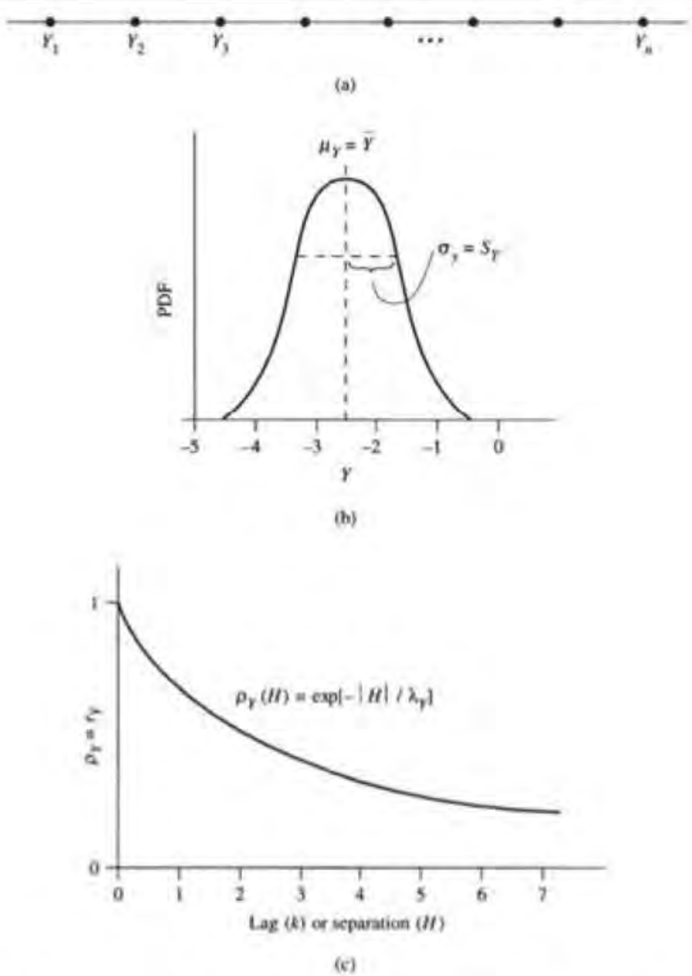
The estimate of the variance of the population is also obtained by the variance of the sampled values, S_y^2, which is found from the following equation:

$$S_Y{}^2 = \frac{1}{n}\sum_{i=1}^{n} (Y_i - \overline{Y})(Y_i - \overline{Y}) \tag{2.42}$$

For a normally distributed population, the probabilistic value is called a probability density function (PDF) and is described by the mean and the variance. The variance is a measure of the degree of heterogeneity of the aquifer. The greater the value, the more heterogeneous the aquifer. The PDF can be represented as a bell-shaped curve with the peak equal to the mean, as in Figure 2.27(b), and the spread of the bell can be defined by either the variance or the standard deviation, S_y, which is the square root of the variance.

If we have measured the value of Y_i at a number of locations and wish to estimate the value Y_j at some other location *j* that is not close to any of the measured values, how can we estimate the value of Y_j? One approach is to say that the most likely estimate of Y_j is the mean of the measured values of Y_i, and the uncertainty in this value is normally distributed with a standard deviation equal to the standard deviation of the measured values, S_y. In doing so we have accepted the **ergodic hypothesis**. This means that there is a 16% chance that the value of Y_j is greater than $\overline{Y} - S_Y$, a 50% chance that it is greater than Y, and an 84% chance that it is greater than $\overline{Y} - S_Y$. In broad terms ergodicity describes a dynamic system which has the same behavior averaged over time as averaged over space.

FIGURE 2.27(a) One-dimensional sequence of log hydraulic conductivity values, Y; (b) probability distribution function for Y; (c) autocorrelation function for Y.



Source: R. A. Freeze et al. 1990. *Ground Water* 28:738–766. Used with permission. Copyright Ground Water Publishing Co.

Hydraulic conductivity values measured at locations close to each other are likely to be somewhat similar. The farther apart the measurements, the less likely that the values will be similar. This is due to the fact that as distances become greater, the chance that there will be a change in geologic formation increases. The function that describes this is the **autocorrelation function**, ρ_Y. The value of the autocorrelation function decreases with the distance between two measurements. An estimate of the autocorrelation function, r_y, can be obtained from the measured sample values by the following equation:

$$r_Y(k) = \frac{1}{S_Y{}^2}\frac{1}{n}\sum_{i=1}^{n}(Y_i - \overline{Y})(Y_{i-k} - \overline{Y}) \tag{2.43}$$

with k, the **lag**, being a whole number representing a position in the sequence away from the i position. Figure 2.27(c) shows an autocorrelation function plotted against the lag. If the lag is zero, then Equation 2.43 reduces to $r_Y = S_Y{}^2 / S_Y{}^2 = 1$. This means that a Y value is perfectly correlated with itself.

The autocorrelation factor can be expressed in terms of either lag, ρ_{Yk} or distance, $\rho_Y(H)$. When a measurement of Y_i is made at position X_i and a measurement of Y_{i-k} is made at position X_{i-k}, the absolute value of $X_i - X_{i-k}$ is called the **separation**, H.

If the autocorrelation function has an exponential form, then it can be expressed as

$$\rho_Y(H) = \exp[-|H| / \lambda_Y] \tag{2.44}$$

where λ_Y, the **correlation length**, is representative of the length over which Y is correlated. It is the distance over which $\rho_Y(H)$ decays to a value of e^{-1}. The **integral scale**, ε_Y, is the area under the curve.

$$\varepsilon_Y = \int_0^{\infty} \rho_Y(H)\,dH \tag{2.45}$$

Integration of Equation 2.45 will show that $\varepsilon_Y = \lambda_Y$, so that the correlation structure can be described by either the correlation length or the integral scale.

The **autocovariance**, τ_{Yk} or $\tau_Y(H)$, is equal to the autocorrelation times the variance.

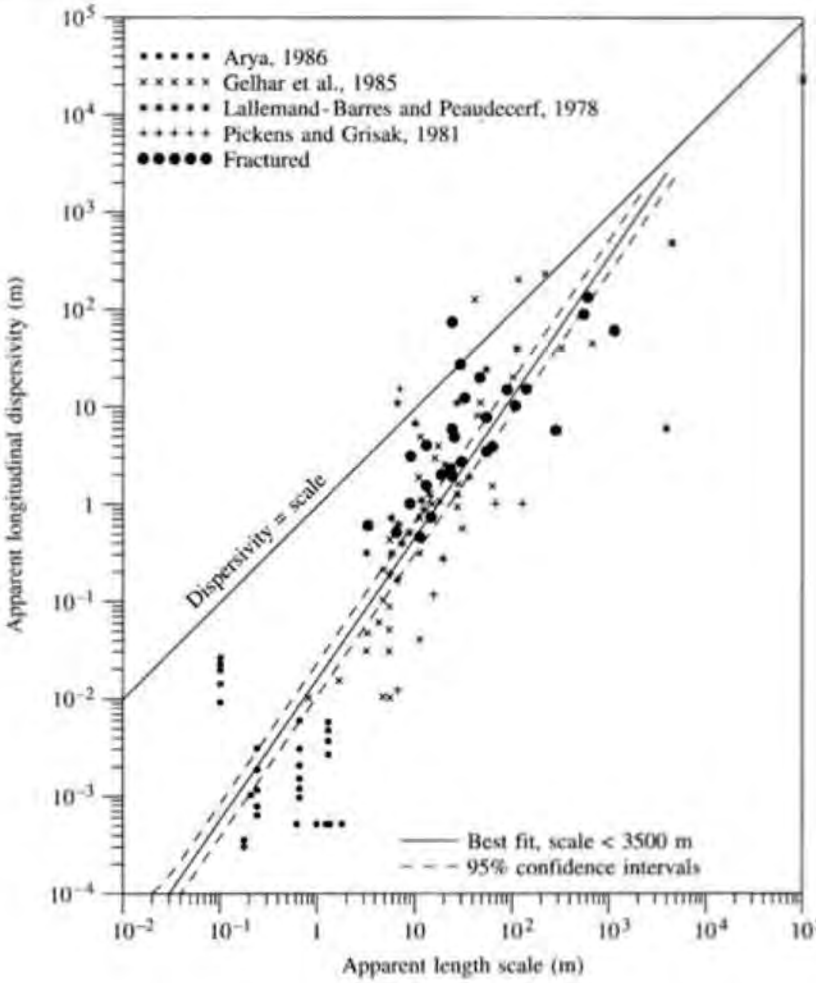
$$\tau_Y(H) = \sigma_Y{}^2 \rho_Y(H) \tag{2.46}$$

We can describe the distribution of heterogeneity of Y by the use of three stochastic functions, μ_Y, σ_Y (or σ_Y^2), and λ_Y. If a stochastic process is said to be stationary, the values of μ_Y, σ_Y (or σ_Y^2), and λ_Y do not vary in space in the region being studied. If the hydraulic conductivity of an aquifer can be described as a stationary stochastic process, the aquifer is uniformly heterogeneous.

2.13.3 Stochastic Approach to Solute Transport

If we accept the idea that we don't know the value of the hydraulic conductivity and the porosity everywhere, then we must accept the idea that it is not possible to predict the actual concentration of a solute that has undergone transport through an aquifer. The best estimate of the concentration is the **ensemble mean concentration**, $\langle C \rangle$, or the mean of all the means of an ensemble of all possible random but equivalent populations, and the associated variance. The movement of a solute body may be described by

FIGURE 2.28 Apparent longitudinal dispersivity from field and laboratory studies as a function of the scale of the study. Results from the calibration of numerical models are not included.



Source: S. Neuman. 1990. *Water Resources Research* 26:1749–1758. Copyright by the American Geophysical Union. Used with permission.

the motion of the center of mass of the body and the second-order spatial moment, or the moment of inertia (Dagan 1988). Hence, from the variance of the log transformed hydraulic conductivity distribution and the correlation length, a simple stochastic model allows predicting an asymptotic macrodispersivity value. However, it is important to note that the process of advective transport dominates macrodispersion. This means that whether one uses a deterministic model or a stochastic model, the large picture of solute transport will emerge, since both account primarily for advective transport, with the dispersion factor tending to smear the leading edge of the plume.

■ 2.14 Regression Analysis of Relationship between Apparent Longitudinal Dispersivity and Field Scale

Neuman (1990) plotted the apparent longitudinal dispersivity as measured in field and lab studies, α_m, as a function of the travel distance, L_s, or apparent length scale

(Figure 2.28). Dispersivities that are measured in the field were considered apparent dispersivities because they were obtained by calculations that depend upon the theory that the observer was using. Also, Neuman (1990) excluded for theoretical reasons all data with an apparent length scale greater than 3500 m (approximately 11,500 ft). Regression analysis showed that although the data are widely scattered, a best-fit line with narrow 95% confidence bands could be obtained. The equation for the line is

$$\alpha_m = 0.0175 L_s^{1.46} \tag{2.47}$$

This line of best fit has a regression coefficient, r^2, of 0.74, which means that it accounts for 74% of the variation about the mean. The other 26% may be due to experimental and interpretive errors or may represent deviation of the real system from that described by Equation 2.47. The 95% confidence intervals about the coefficient of 0.0175 are 0.0113and 0.0272 and the 95% confidence intervals about the exponent of 1.46 are 1.30 and 1.61.

Equation 2.47 obtained by Neuman (1990) was based on data that he considered to be highly reliable. In doing so he discarded data that were less reliable, such as that obtained by the calibration of numerical models. Neuman recognized that as the flow path grew longer, the same equation relating apparent longitudinal dispersivity to field scale could not be used, so that he used two linear equations, one for flow distances less than 100m (328 ft) and one for flow distances greater than 100m (328 ft) (Equation 2.47). However, a discontinuity occurs in his method at 100m (328 ft); i.e., the two equations give different answers. Neuman and Di Federico (2003) demonstrated experimentally and theoretically that the scaling behavior of hydrogeologic variables is impacted strongly by their scale of spatial resolution.

Xu and Eckstein (1995) have overcome these problems by assigning different degrees of reliability to data: low, medium and high. They were then able to obtain a nonlinear relationship based on a regression analysis using all available data. The resulting equation had a correlation coefficient of 0.72, which is similar to that obtained by Neuman (1990) using only highly reliable data. Neuman (1990) also did not consider any data with a flow field longer than 3500m (~11,500 ft) because he did not consider it to be reliable, while Xu and Eckstein (1995) included these data.

The equation of Xu and Eckstein is:

$$\alpha_m = 0.83(\log L_s)^{2.414} \tag{2.48}$$

If one examines Figure 2.24, which includes data of low reliability, it appears that as the field scale increases, the rate of change of dispersion decreases. Being nonlinear as plotted on log-log paper, Equation 2.48 also has a decreasing rate of change of dispersion with increasing field scale. At a field scale of greater than a few thousand meters there is very little change in apparent dispersion with distance.

By analyzing jointly dispersivity values derived from models having variable scales of spatial resolution, Schulze-Makuch (2005) proposed a power law relationship that empirically best described the dispersivity data in regard to scale of measurement:

$$\alpha_L = cL^m$$

where c is a parameter characteristic for a geological medium, m is a scaling exponent, and L is the flow distance. The scaling exponent for consolidated and unconsolidated geological media varied between 0.40 and 0.92, and 0.44 and 0.94, respectively. For example, an unconsolidated sandy aquifer: c = 0.20 and m = 0.44. For a distance of 100 m (328 ft), the longitudinal dispersivity value is $\alpha L = 1.6$ m. Similar equations exist for other types of aquifers. No upper bound on the relationships was apparent for a flow distance up to ~10,000 m (~6 miles) for all media except for granites where this relation currently can only be extended to a flow distance of 100 m (328 ft). However, the relationship proposed by Schulze-Makuch (2005) was criticized by Neuman (2006) for neglecting the spatial resolution scales of the models from which the dispersion data had been derived. A theoretical interpretation of the scaling behavior has been summarized in a nonmathematical way in the review paper of Neuman and Di Federico (2003).

2.15 Deterministic Models of Solute Transport

Although workers in stochastic theory have asserted that the theoretical basis for the deterministic advective-dispersive solute transport equation is suspect except for long times and large distances (Anderson 1984), it has been used with a great deal of success in many field and model applications. Today, mathematical transport and fate modeling of contaminants in groundwater and soils has become an important tool for the interpretation of contaminated sites, the development of remedial strategies, and the human health risk assessment process.

Over the past decades, many papers and textbooks have been written about deterministic models for contaminant transport modeling (e.g., Anderson and Woessner 1991; Zheng and Bennet 2002). In general, a deterministic mathematical model simulates groundwater flow and/or solute fate and transport indirectly by means of a set of governing equations, such as Darcy's law and law of mass conservation, thought to represent the physical processes that occur in the system (Anderson and Woessner 1991). The first step in the modeling process is to develop a conceptual model that is simpler than reality. Simplification can be achieved, for example, by combining strata with similar hydrogeologic properties into a single layer or aquifer. The next step requires translating the conceptual model into a mathematical model, which can then be solved in a computer simulation. A numerical mathematical model solves the underlying governing partial differential equations (PDEs) within a set of suitable boundary conditions, and if the transport problem is of transient nature, initial conditions. This step usually requires that additional simplifying assumptions have to be made to reduce the complexity of the mathematical model. For example, a coarser grid can be defined in parts of the flow domain where less accuracy is required, or fixed value boundaries (e.g., no-flux or constant head boundaries) can be defined, or the length of the simulation time steps can be manipulated to reduce the number of computations. These adjustments make the model amenable to either exact or numerical solution, but the modeler must weigh the risk of oversimplifying the flow domain against the problem of no longer reproducing the system adequately. A parsimonious model therefore is a model that accomplishes a desired level of explanation or prediction with the fewest predictor variables possible.

The flow and transport equations underlying the model are solved at discrete points within the flow domain. The two classical choices for the numerical solution of PDEs are the finite difference method (FDM) and the finite element method (FEM).

Other methods exists, such as the finite volume method (FVM) or the analytic element method (AEM), but models build around these numerical solution schemes are currently not used widely. A detailed discussion of numerical methods is beyond the scope of this textbook and the reader is referred to Peiro and Sherwin (2005).

The current standard FDM program is MODFLOW, which was developed by the U.S. Geological Survey (USGS) for three-dimensional flow modeling (McDonald and Harbaugh 1988). Over the years, many modules have been added to the MODFLOW program, including modules to simulate coupled groundwater/surface-water systems, solute transport, variable-density flow (including saltwater), aquifer-system compaction and land subsidence, parameter estimation, and groundwater management (USGS 2014). MODFLOW can be used in conjunction with MT3DMS, which is a 3D multi-species transport model (Zheng et al. 2010). MT3DMS solves the advection-dispersion-reaction equation based on the methods of characteristics, MOC (Konikow et al. 1994). The FDM model domain is subdivided or discretized into a grid of rectangular blocks or cells within which the physical properties of the domain are assumed to be homogeneous. The block structure of the FDM models often make them difficult to adopt to more complex modeling domains. Under those circumstances, FEM models provide greater flexibility in design because the modeling domain is discretized by triangular elements. Common FDM programs include SUTRA, a variable-density, variably-saturated flow, solute or energy transport model by the U.S. Geological Survey (2015a) or FEFLOW, a commercial modelling environment for subsurface flow, solute and heat transport processes. Another versatile commercial FVM model is HYDRUS 2D/3D, which also offers unsaturated flow modeling capabilities (Simunek et al. 1999; Simunek et al. 2006) and modeling of agricultural pollutants especially those from nonpoint source pollution stemming from plant and animal production (Simunek et al. 2013). There are many more noteworthy models available and many are in public domain. The U.S. Geological Survey maintains a website from which public domain software packages for the simulation of groundwater flow and transport can be downloaded (USGS 2015b).

A model study by Davis (1986) demonstrates that deterministic models can be developed that incorporate heterogeneities. He modeled two aquifers with identical boundary conditions (Figure 2.29). One was uniform (Figure 2.30(a)) and one had variable transmissivity in the form of more permeable channels (Figure 2.30b). The deterministic model, based on the two-dimensional solute-transport equation, was used with small values of α_L and a α_T, 0.0003 m (0.01 in), and 0.00009 m (0.003 in), respectively. The resulting solute plume in the uniform media is very long and narrow. See Figure 2.31(b). If larger values of α_L and α_T are used—3 m (10 ft) and 1 m (3 ft), respectively—then a much broader plume results. See Figure 2.31(a). However, if the heterogeneous aquifer is used with the small values of dispersivity, the resulting plume, shown in Figure 2.31(c) has a size very similar to that created in the uniform media by using large values of dispersivity. This demonstrates that if deterministic models include the aquifer heterogeneities, then it may be possible to use dispersivity values that are more on the order of lab-scale values. Davis (1986) used the advective-dispersion equation in a model with varying transmissivities and with a value of α_L of only 0.01 m (0.4 in) was able to reproduce a solute plume that extended over a flow length of about 500 m (1,640 ft). He found that a fine mesh for the finite-difference model grid was necessary for accurate results. Figure 2.32 compares the results of his model results with the field data.

FIGURE 2.29 Finite-difference grid and boundary conditions for a deterministic model of solute transport.

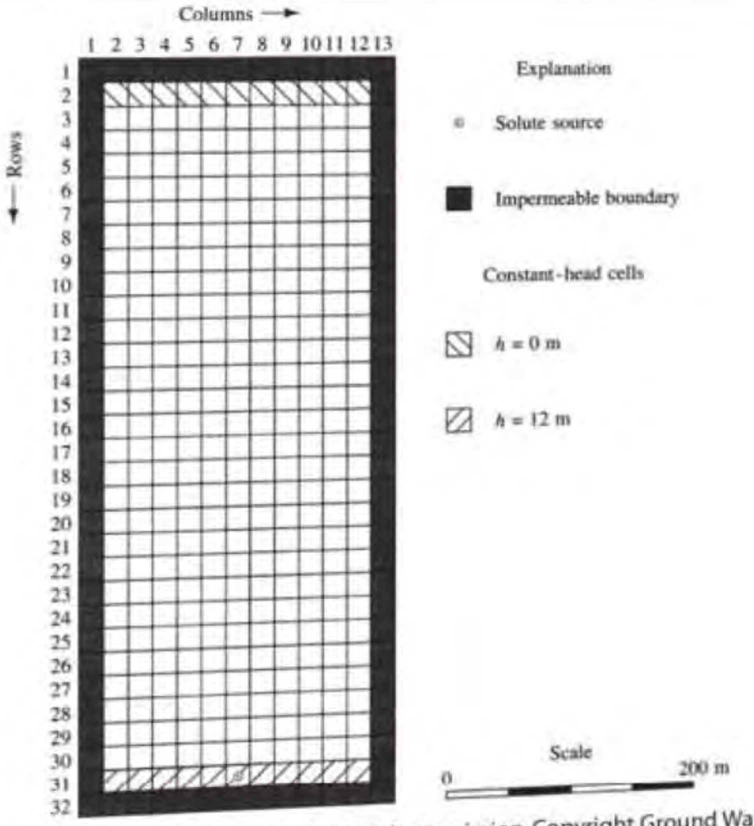


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FIGURE 2.30 Model areas for finite difference solute transport model with (a) uniform transmissivity and (b) with heterogeneous transmissivity.

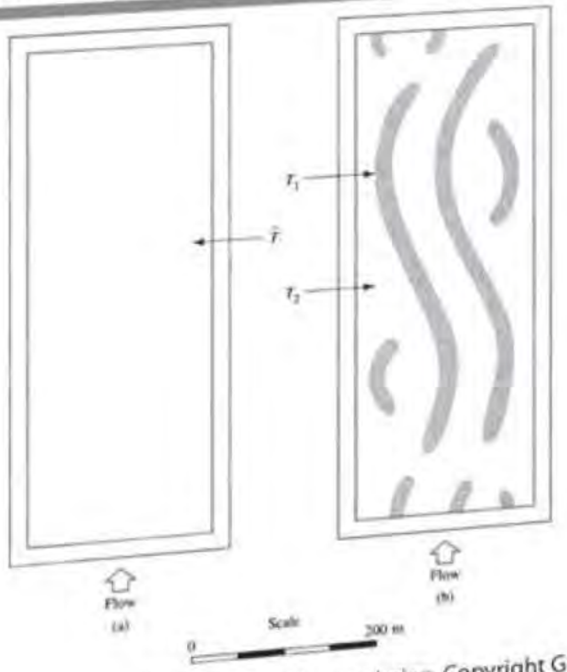

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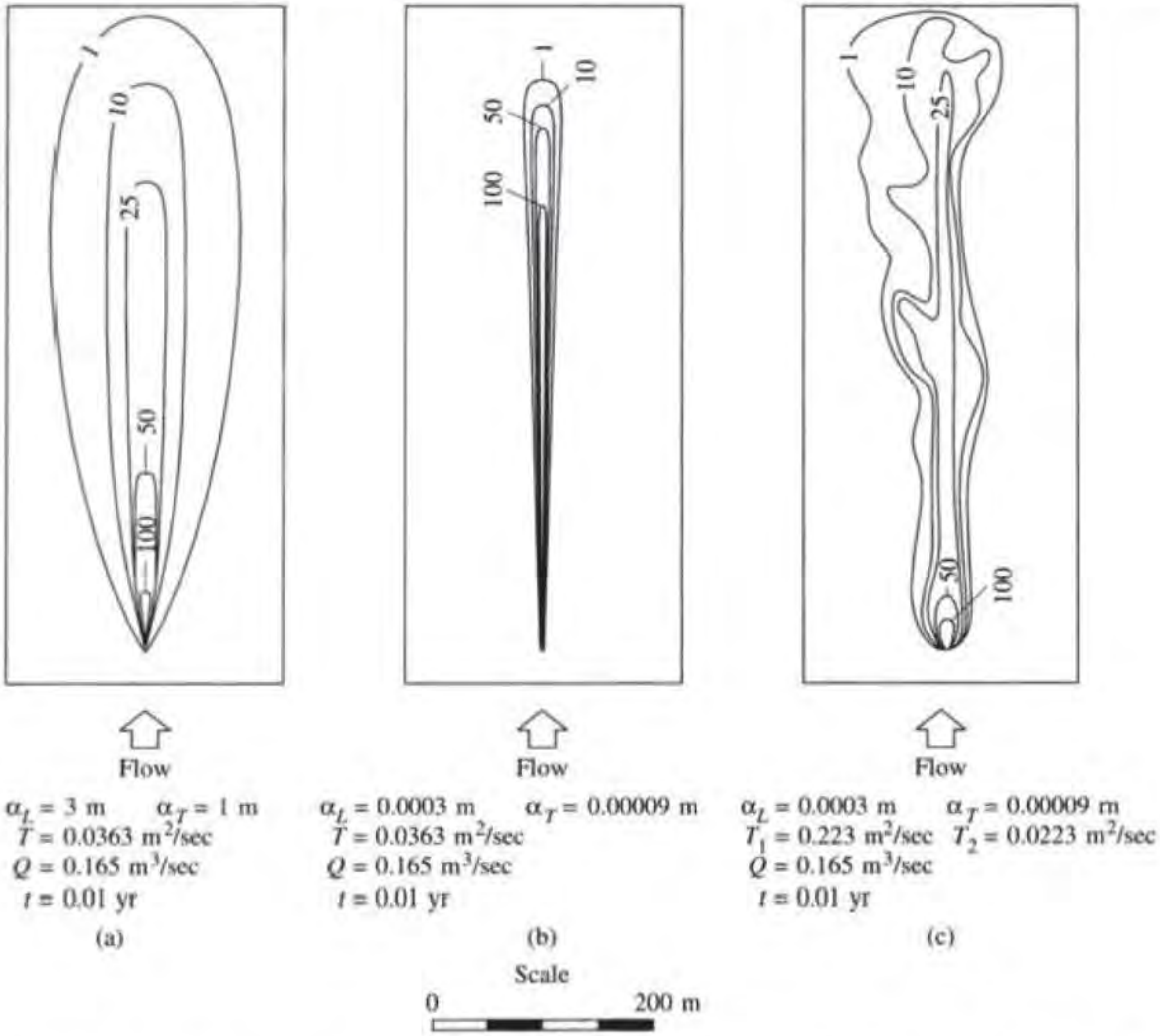
FIGURE 2.31 Model results for finite-difference solute-transport model. (a) Uniform media with large dispersivity values, (b) uniform media with small dispersivity values, and (c) heterogeneous media with small dispersivity values.



$\alpha_L = 3$ m $\alpha_T = 1$ m
$T = 0.0363$ m^2/sec
$Q = 0.165$ m^3/sec
$t = 0.01$ yr
(a)

$\alpha_L = 0.0003$ m $\alpha_T = 0.00009$ m
$T = 0.0363$ m^2/sec
$Q = 0.165$ m^3/sec
$t = 0.01$ yr
(b)

$\alpha_L = 0.0003$ m $\alpha_T = 0.00009$ m
$T_1 = 0.223$ m^2/sec $T_2 = 0.0223$ m^2/sec
$Q = 0.165$ m^3/sec
$t = 0.01$ yr
(c)

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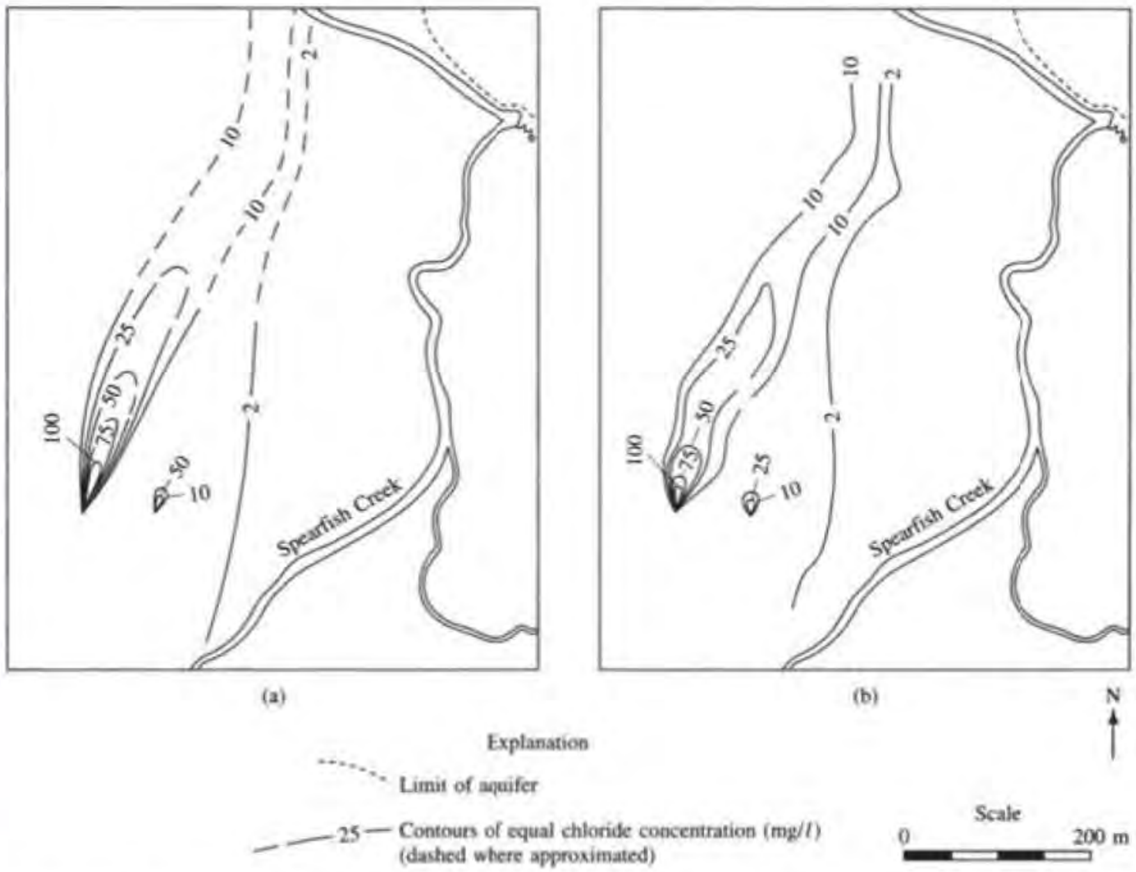
Case Study: Borden Landfill Plume

Probably the best known subsurface contaminant transport field test site is located on the Canadian Forces Base in Borden, Ontario (Sudicky and Illman 2011). An abandoned landfill in a shallow sand aquifer at Borden has been extensively studied (Cherry 1983; Macfarlane et al. 1983) and Frind and Hokkanen (1987) made a very interesting study of the plume based on a deterministic model.

The landfill was active from 1940 to 1976 and covers about 5.4 ha to a depth of 5 to 10 m (16 to 32 ft). Figure 2.33 shows the location of water table wells and multilevel sampling devices. The multilevel sampling devices are concentrated along the long axis of the plume of groundwater contamination. The vertical location of the sampling points along cross section A-A′ are shown in Figure 2.34. The aquifer is about 20 m (65 ft) thick beneath the landfill and thins to about 9.5 m (31 ft) in the direction of groundwater flow. The aquifer consists of laminated fine to medium sand. An average hydraulic conductivity of 1.16×10^{-2} cm/sec horizontally and 5.8×10^{-4} cm/sec vertically was used in the model with a porosity of 0.38. In 1979 a very extensive study of the water quality of the plume was conducted. Figure 2.35 shows the plume of chloride contamination along cross section A-A′. In 1979 the plume extended about 750 m (2,460 ft) from the landfill and had sunk to the bottom of the aquifer and then moved laterally with the flowing groundwater. The sinking of the plume is believed to be caused by recharge concentrated in a sand pit to the north of the landfill, which is in the direction of flow.

FIGURE 2.32 Comparison of (a) field observations at solute plume in an aquifer and (b) solute plume as computed by finite-difference solute-transport model for a heterogeneous aquifer.



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The finite-difference grid system for the cross-sectional model is shown in Figure 2.36. Equipotential lines for observed conditions were essentially vertical (Figure 2.37). The model was calibrated against the water-table contours for steady-state conditions.

Sensitivity analyses were performed to determine the impact of varying α_L and α_T. Field tests had indicated that the value of α_L at the site is on the order of 5 to 10 m (16 to 32 ft) (Sudicky et al. 1983). Figure 2.38 shows the sensitivity of the plume to the value of α_T. The value of α_L was kept at 10 m (32 ft) and α_T was varied from 0.005 m (0.02 in) to 1.0 m (3 ft). It can be seen that the shape of the plume is very sensitive to the value of α_T. With a high value of α_T, the plume spread through the entire vertical thickness of the aquifer, whereas with a low value it tended to sink toward the bottom. Figure 2.39 illustrates the fact that the plume was not very sensitive to changes in the value of α_L over the range tested. The value of α_T was kept constant at 0.01 m (0.4 in), whereas α_L varied from 2.5 to 20 m (8 to 65 ft). This figure is slightly misleading in that there is a 10:1 vertical exaggeration, so that the vertical spreading is more obvious than the horizontal. Also, the value of α_T was varied by a factor of 200, whereas α_L was varied only by a factor of 8.

FIGURE 2.33 Location of landfill at Canadian Forces Base, Borden, Ontario, showing location of cross section and monitoring network.

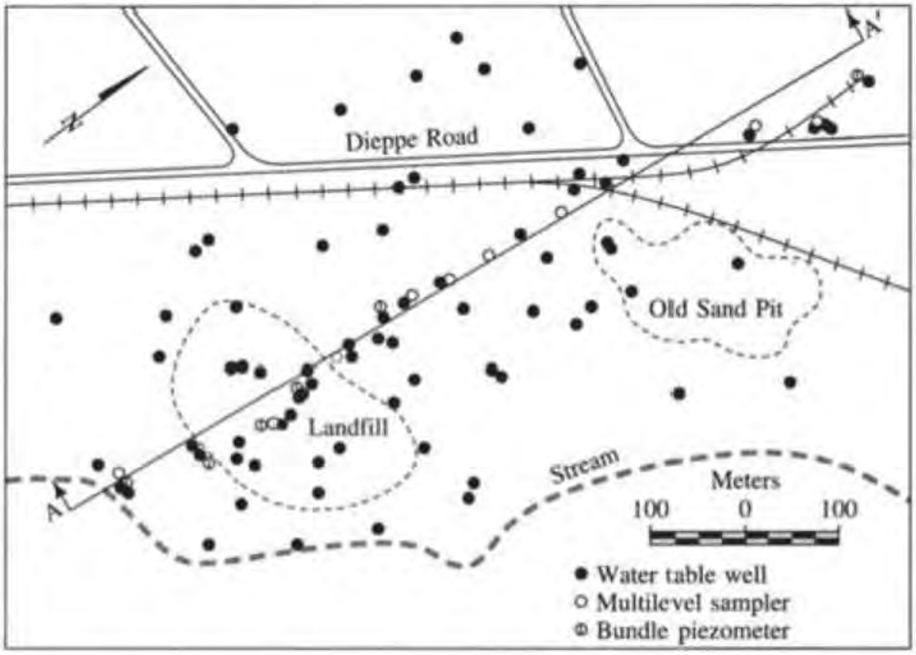

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FIGURE 2.34 Cross section of aquifer at the Border landfill showing the location of multilevel monitoring devices.

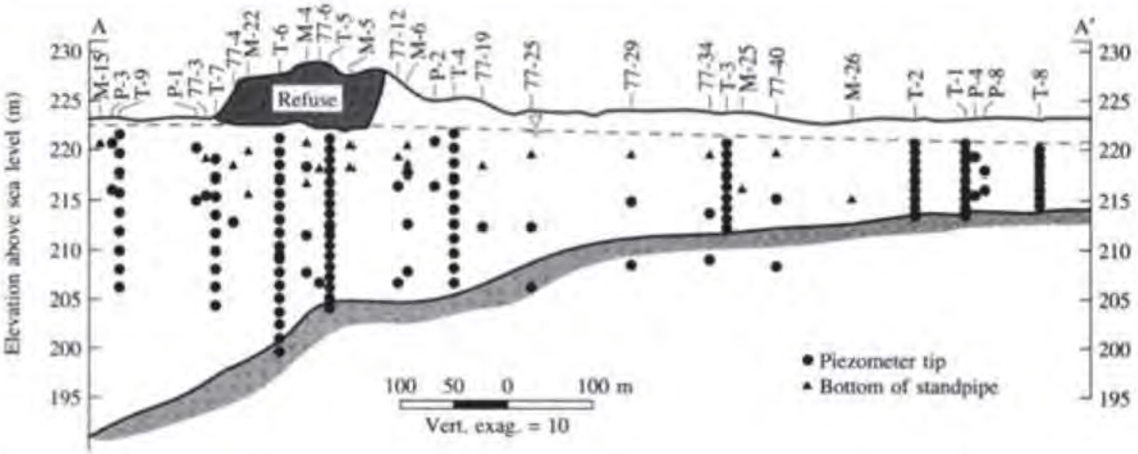

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FIGURE 2.35 Chloride plume along the Border landfill across section in 1979. Values are in milligrams per liter.

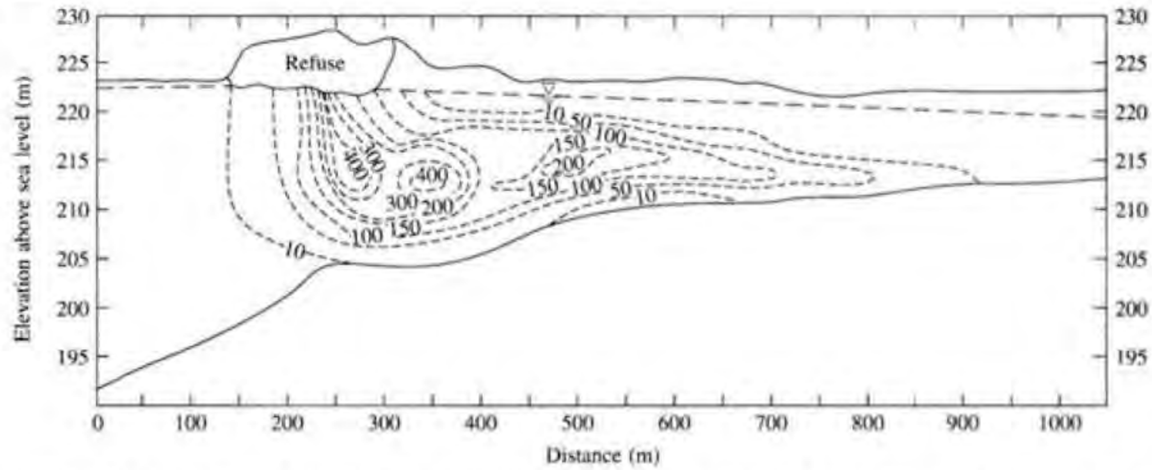

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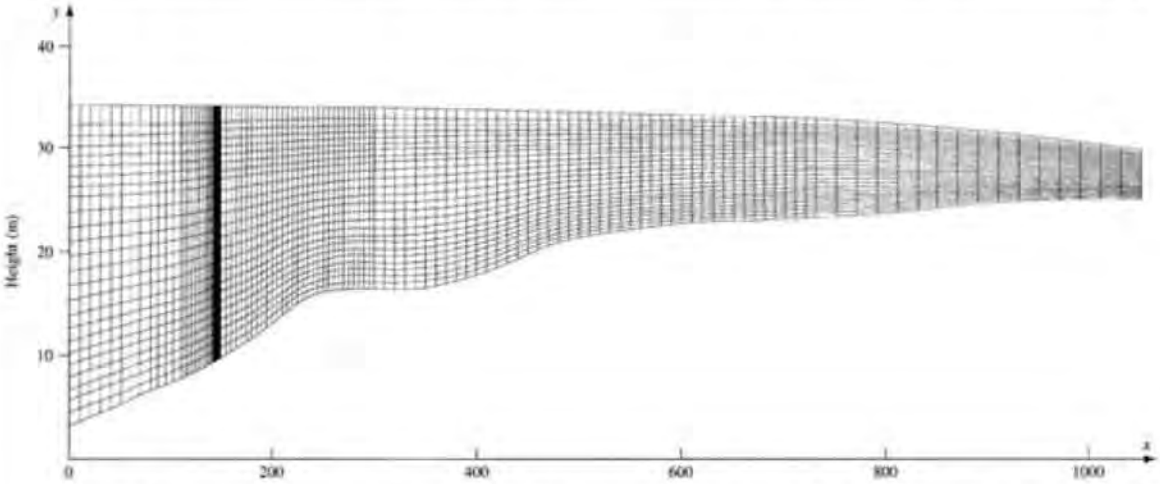
FIGURE 2.36 Finite-difference grid for Borden landfill solute transport model.



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Additional sensitivity analyses were conducted with respect to the water table boundary conditions and the concentration, size, and growth pattern of the source. The authors found that in order to reproduce the observed distribution, a source history that included multiple periods of high concentration was needed. Figure 2.40(a) shows the shape of the observed plume, Figure 2.40(b) illustrates the shape of a plume generated by a source with a history in which the concentration gradually increased (smooth source concentration), and Figure 2.40(c) contains the computed plume with the best match to the observed plume. It was generated by a run of the model in which the source concentration had two different periods of peak concentration. Although the solution was not unique—that is, several different combinations of model inputs might yield the same output—the shape of the plume could be reproduced with good accuracy. This was especially true at the leading edge of the plume, which is the most important part from the standpoint of predicting the movement of the plume into uncontaminated areas of the aquifer.

FIGURE 2.37 Equipotential lines from the calibration of the Borden landfill solute-transport model; values in meters above datum.

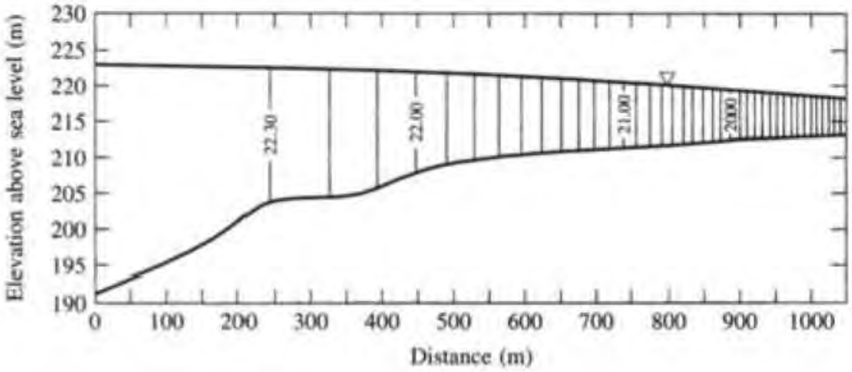

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FIGURE 2.38 Sensitivity analysis of the Borden landfill solute-transport model with respect to transverse dispersivity.

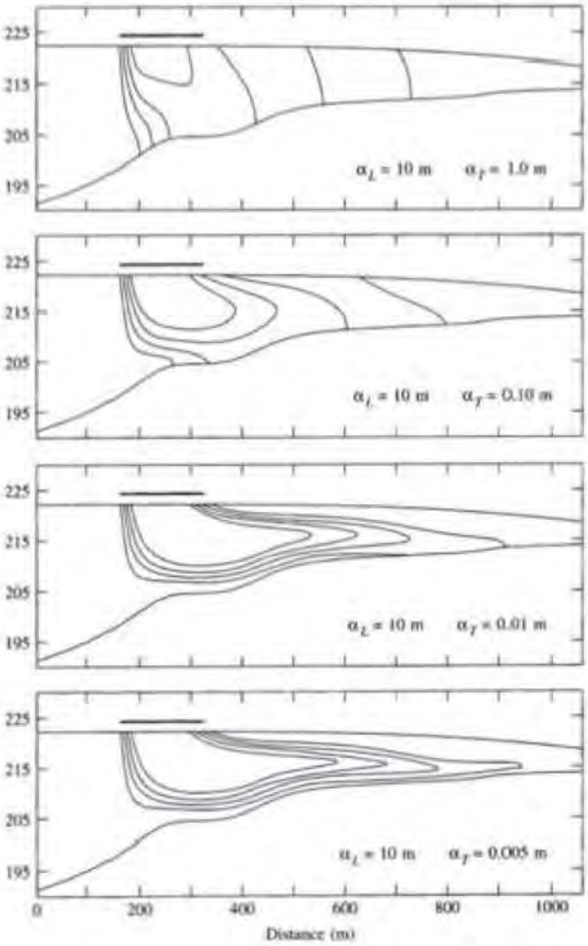

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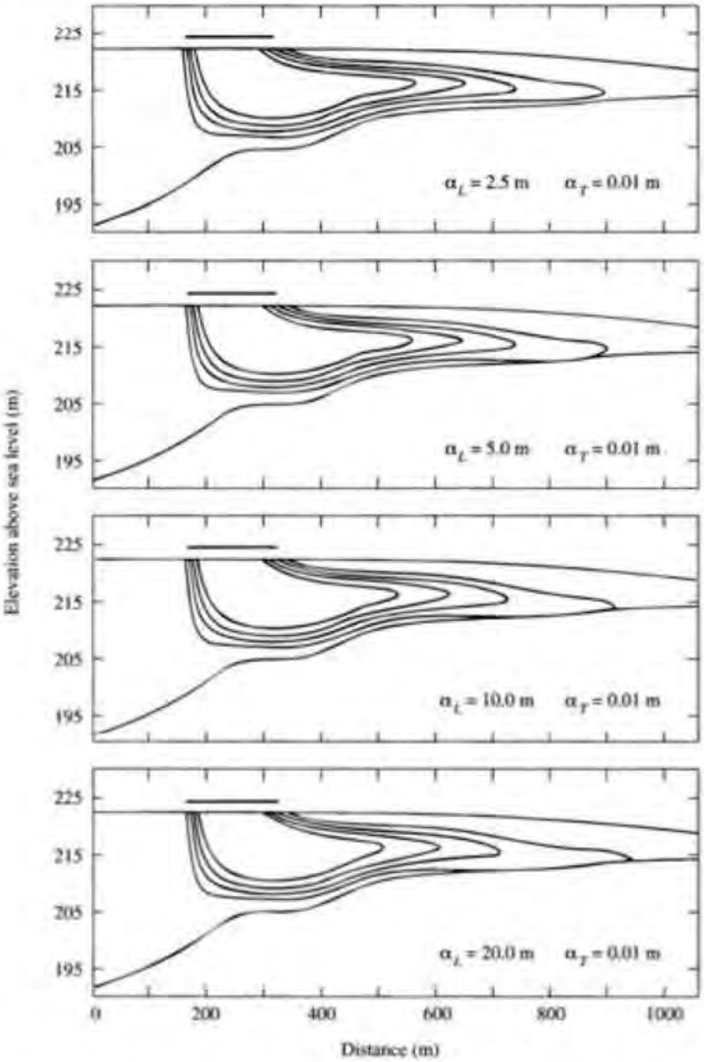
FIGURE 2.39 Sensitivity analysis of the Borden landfill solute-transport model with respect to longitudinal dispersivity.



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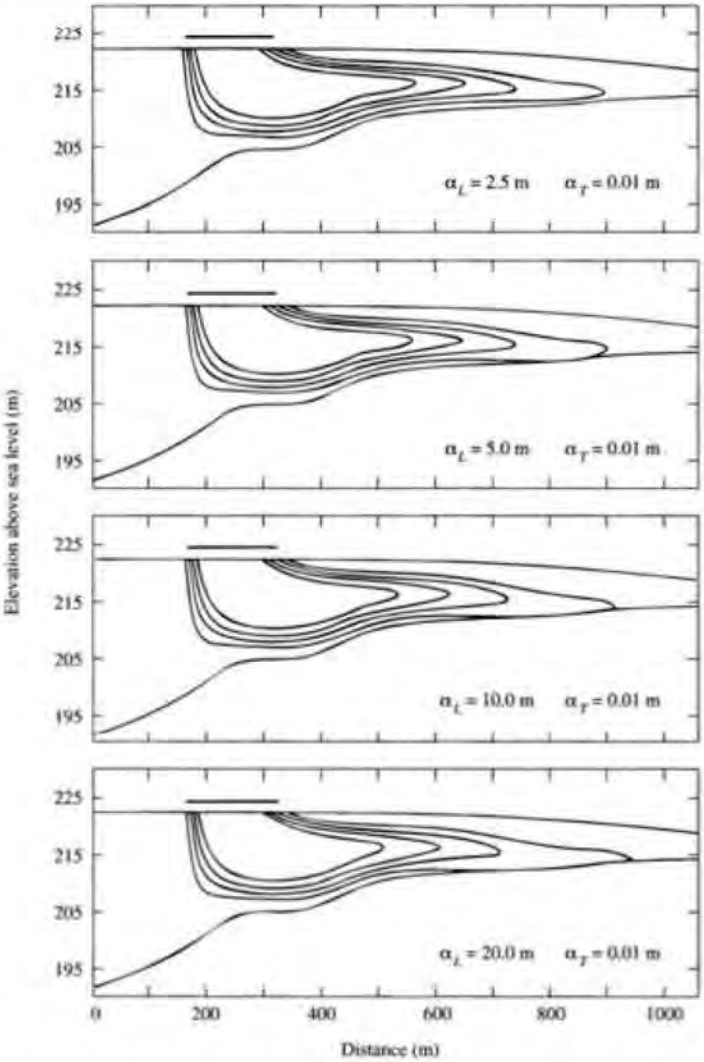
2.16 Transport in Fractured Media

Solute transport in fractured rock media is as important a process as transport in porous media. Understanding fluid flow and mass transport in fractured rocks is essential for assessing the groundwater resources of hard-rock aquifers and predicting the movement of hazardous chemicals if contamination occurs. Transport in fractured media is also important when assessing the suitability of underground sites for hazardous waste disposal, such as the heavily investigated former candidate site for a nuclear waste repository at Yucca Mountain in Nevada. However, less research has been done on this topic than on transport in porous media. One reason may is that existing theory of fluid flow through porous media is of limited usefulness when applied to fractured

FIGURE 2.39 Sensitivity analysis of the Borden landfill solute-transport model with respect to longitudinal dispersivity.



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Berkowitz et al. (1988) suggested that solute transport in fractured media can be considered at a number of different scales. A very-near-field scale would be a single fracture near the source. A near-field scale would include a few fractures near the source. At a larger scale, the far field, the fracture network and the porous media matrix would have separate, discernible impacts on flow. At a very-far-field scale, which exists at considerable distance from the source, the entire flow domain can be considered as an equivalent porous medium in which the repeating fractures became large pores.

A number of different approaches to solute transport in fractured media have been attempted. These include analysis of transport in a single fracture in which effects of the transport in the fractures as well as interactions with a porous matrix are considered (e.g., Grisak and Pickens 1980; 1981; Tang et al. 1981; Rasmuson and Neretnieks 1981; Rasmussen 1984; Sudicky and Frind 1984). Sudicky and Frind (1982) and Barker (1982) examined transport in a media that consists of equally spaced fractures in a porous media. Endo and others (1984) made a deterministic study of flow in an irregular network of fractures contained in an impermeable host rock, whereas Schwartz et al. (1983) and Smith and Schwartz (1984) approached the same problem using a stochastic model. Berkowitz et al. (1988) and Schwartz and Smith (1988) examined the conditions under which the porous media matrix and the fractures can be considered to be a continuum that is representative of an equivalent porous media. Raven et al. (1988) made a field study of flow through a single fracture to test a model that incorporates the effects of nonflowing water in the fractures. Tsang et al. (1988) and Moreno et al. (1988) examine fracture flow on the basis of the assumption that most of the flow is concentrated in a few channels.

Dietrich et al. (2005) proposed a multi-continuum model in which separate, coupled hydraulic components in a heterogeneous aquifer are modeled. It is assumed that each component is distributed continuously in space and satisfies the condition of a porous medium (Bear and Bachmat 1990). For fracture matrix systems, this could be two fracture continua, such as a micro- and macro-fracture system, and a matrix continuum with appropriate equivalent parameters. The matrix and fractures are locally idealized as continua and the fractures are implemented discretely at their actual locations within the domain. It is obvious that the amount of data required to set up a discrete model of the actual domain is very large and to some extent not measureable. Consequently, the discrete model concept is preferentially used for relatively small domains and it is a suitable tool for principle studies of flow and transport processes (Dietrich et al. 2005).

One of the first considerations in dealing with fracture flow is deciding how to treat flow in a single fracture. Some authors (e.g., Tang et al. 1981; Schwartz and Smith 1988) assume that the fluid in a fracture is all moving at a constant velocity. Conversely, Endo et al. (1984) treated flow in a fracture to be two-dimensional, with a parabolic velocity profile across the width of the fracture, as shown in Figure 2.41. Transport within a single fracture is due to advection, which occurs at different rates, depending upon the position between the parallel walls of the fracture, and molecular diffusion, both normal and parallel to the flow direction.

FIGURE 2.40 Comparison of (a) the observed chloride plume at the Borden landfill with (b) the chloride plume simulated by the solute transport model with a smooth source concentration and (c) the chloride plume simulated by the solute transport model with a doubly peaked source concentration.

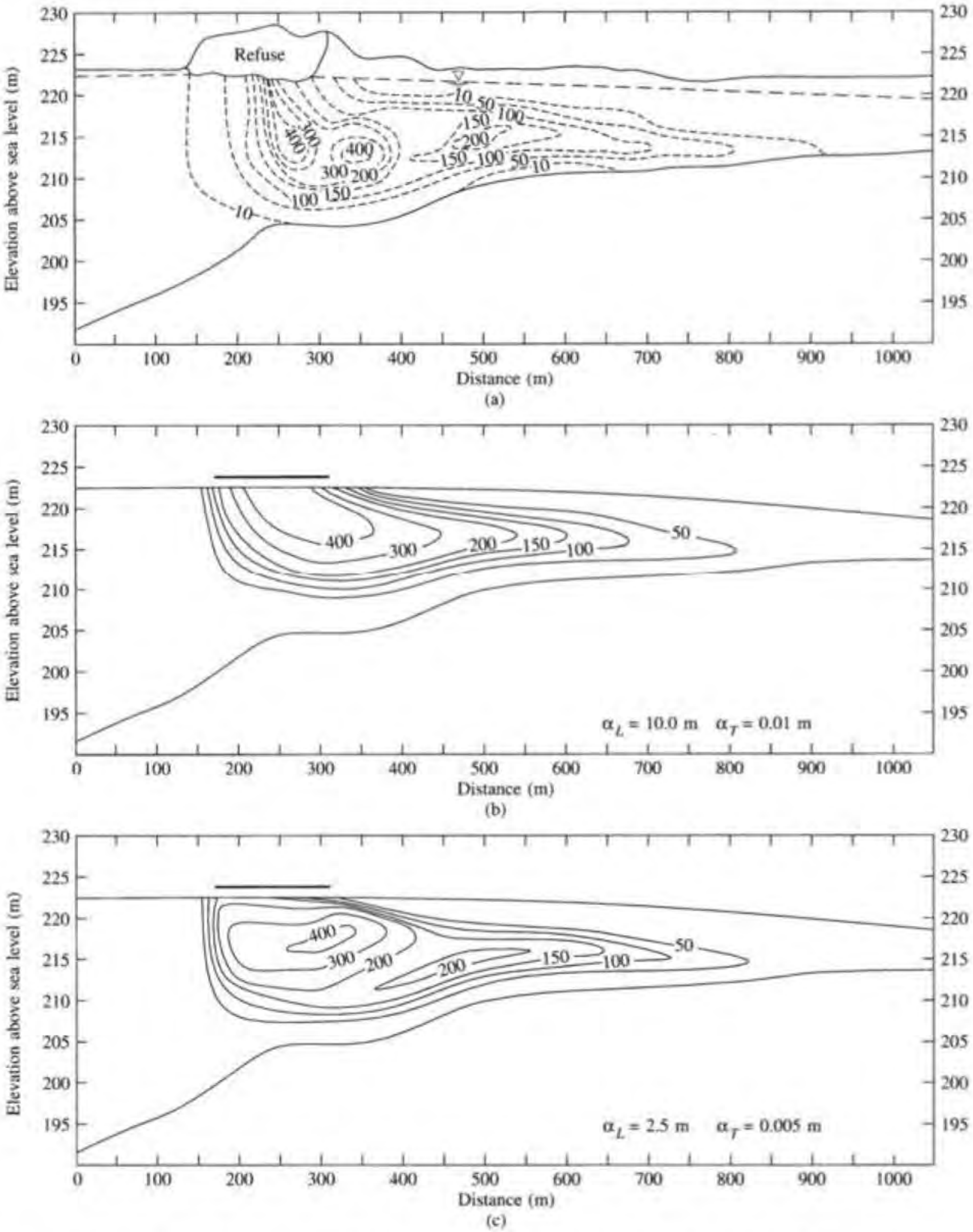

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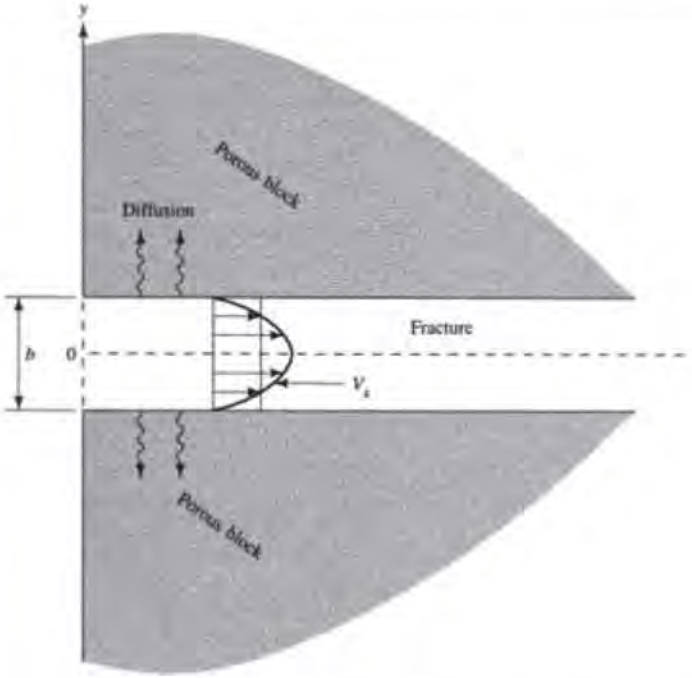
FIGURE 2.41 Horizontal distribution of flow in a vertical fracture and diffusion into the porous media matrix.



Hull et al. (1987) examined the conditions whereby diffusion within the fracture needs to be considered. In a fracture with parallel sides, the solute transport within the fracture is described by

$$\frac{\partial C}{\partial t} = D^*\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2}\right) - 6V\left[(\tau) - (\tau)^2\right]\frac{\partial C}{\partial x} \tag{2.49}$$

where

V = average fluid velocity in a fracture
τ = fractional transverse position in a fracture

At high flow rates, advection will dominate and the concentration will follow the velocity profile of Figure 2.41. At low velocities, diffusion will be important, since the concentration gradient at the solute front will be high and the distance will be short. Under these conditions, diffusion will homogenize the solute across the width of the fracture.

If L is the length of the fracture between cross fractures and β is the aperture of the fracture, the fracture residence time is L/V. This can be compared with $(\beta/2)^2/D$ to determine if diffusion needs to be considered (Crank 1956). If diffusion induces a change in the tracer concentration of less than 2% over a distance of 10% of the width of the fracture, the diffusion can be considered negligible, and the residence time in the fracture will be

$$\frac{L}{V} < 0.003\frac{(\beta/2)^2}{D} \tag{2.50}$$

If diffusion affects the tracer concentration to the extent that the tracer front is at 98% of the equilibrium value at all points across the fracture, the diffusion has homogenized the front, and the residence time in the fracture will be

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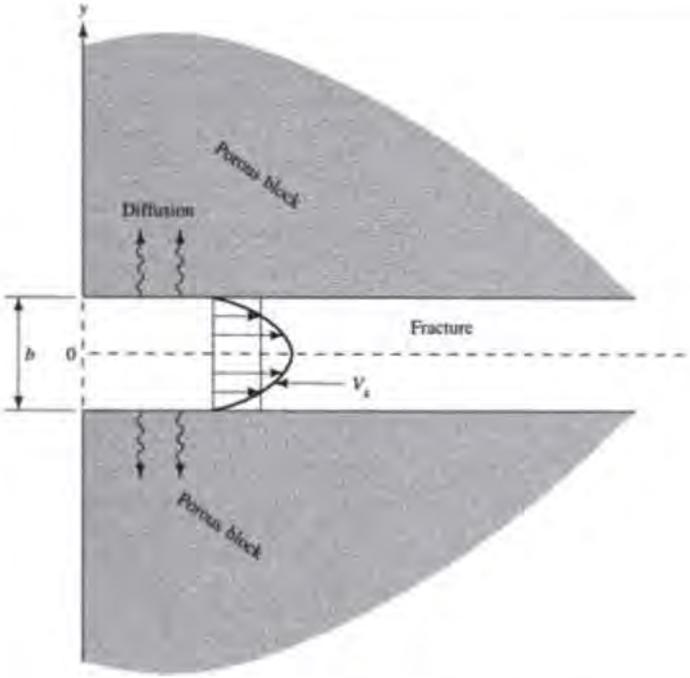

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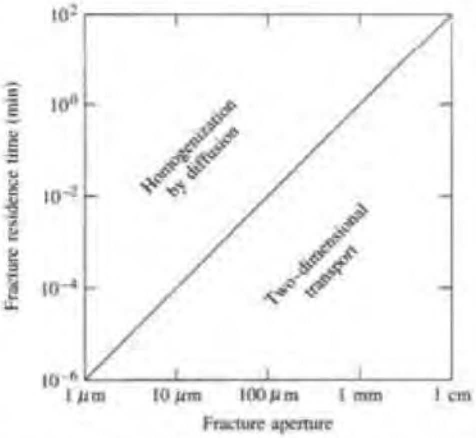
FIGURE 2.42 Fracture residence time necessary for homogenization of the tracer across the fracture width by molecular diffusion.



Source: Modified from L. C. Hull, J. D. Miller, and T. M. Clemo. 1987. *Water Resources Research* 23:1505–1513. Copyright by the American Geophysical Union. Reproduced with permission.

$$\frac{L}{V} < 0.05\frac{(\beta/2)^2}{D} \tag{2.51}$$

Figure 2.42 indicates the circumstances under which fracture flow can be considered to be one- or two-dimensional. Fracture residence time (L/V) is plotted against fracture aperture on this figure, which is based on a diffusion coefficient of 1.7×10^{-9} m^2/sec (1.93×10^{-8} ft^2/sec). The figure shows the conditions under which diffusion will homogenize the flow so that the transport within the fracture can be treated as one-dimensional (uniform conditions across the aperture). However, diffusion will still spread the tracer in advance of the advecting water. For even large fractures of 1mm aperture, this will occur with a residence time of 1min or more. This suggests that for most flow situations, one does not need to consider the velocity distribution across the fracture.

When the flow in a fracture is homogeneous, the mass transport can then be described by the one-dimensional advection-dispersion equation with the longitudinal dispersion coefficient equal to (Hull et al. 1987)

$$D_L = \frac{(V\beta)^2}{210D} \tag{2.52}$$

One approach to solute transport modeling is to determine the flux of water through the fractures and then use a numerical technique known as a random walk model to simulate diffusion of the solute (Hull et al. 1987). This ignores any diffusion into the porous media matrix. According to Witherspoon et al. (1980), flow through a fracture can be described by Darcy's law using an equivalent hydraulic conductivity for a fracture, K_f given by

$$K_f = \frac{\rho g}{12\mu}\beta^2 \tag{2.53}$$

The quantity of flow, Q, can be found from the cubic law

$$Q = \frac{\rho g}{12\mu} Ia\beta^3 \tag{2.54}$$

where

g = acceleration of gravity
I = hydraulic gradient along the fracture
a = width of the fracture-that is, the third dimension after length and aperture
μ = viscosity of fluid

If the velocity in the channel needs to be described in two dimensions, this can be done with three equations: one for the maximum velocity in the center of the fracture, one for the flow velocity profile across the aperture, and one for the vertical velocity profile in the fracture.

The maximum velocity can be found from (Hull et al. 1987):

$$V_x(\max) = \left[1.5 + 1.1664\left(\frac{a}{\beta}\right)^{-1.0557}\right]V \tag{2.55}$$

The velocity profile across the aperture is given by.

$$V_x(y) = 4\left(\tau - \tau^2\right) \tag{2.56}$$

where τ = fractional transverse position in a fracture, y/β.

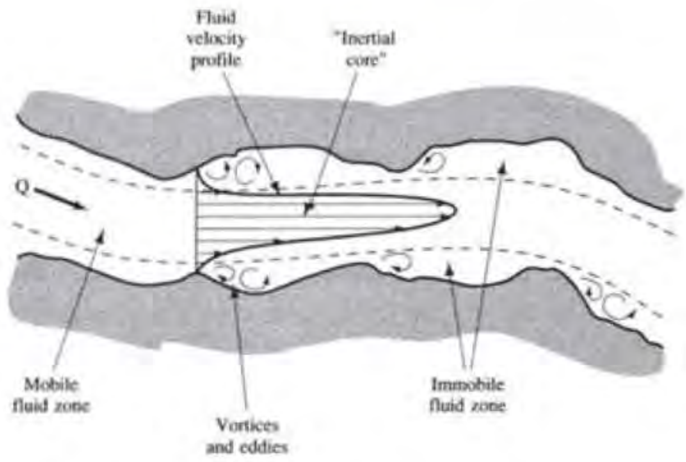
The vertical velocity profile is given by

$$V_x(\zeta) = 15.56\zeta - 97.72\zeta^2 + 308\zeta^3 - 513\zeta^4 + 43l\zeta^5 - 143.7\zeta^6 \tag{2.57}$$

where ζ = fractional vertical position in a fracture, z/a.

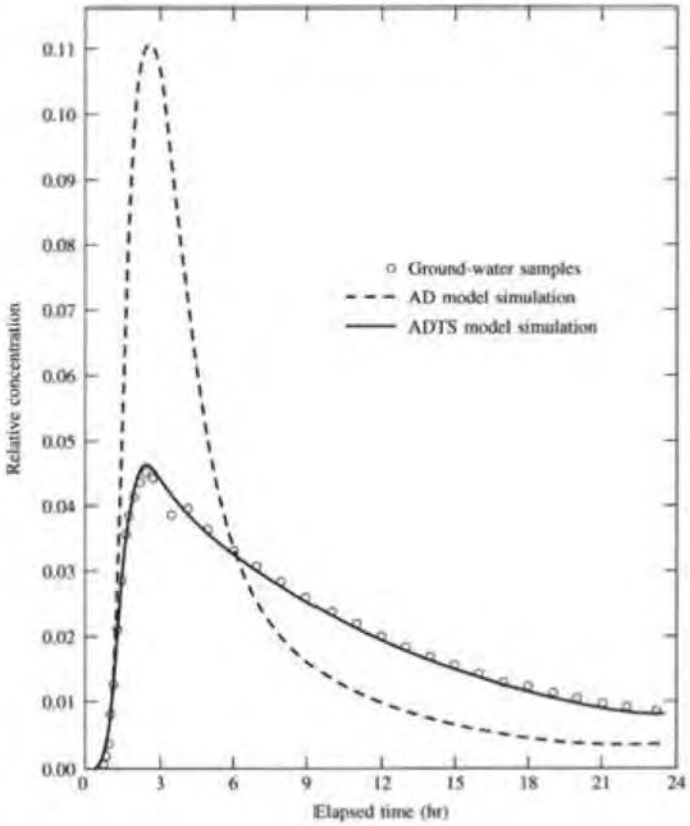
Raven et al. (1988) pointed out that the fractures through which flow occurs are not smooth, parallel plates but have irregular walls that promote the formation of zones along the edge of the fracture where the water is immobile (Figure 2.43). The fluid moves through the mobile zone, but the solutes can diffuse into the immobile fluid zones. The solute would be stored in the immobile fluid during the early part of solute transport and would be released from storage if the solute concentration in the mobile fluid would decrease—for example, as might happen during the latter part of a slug injection test. They derived an advection-dispersion equation for mass transport in the fracture with "transient solute storage in the immobile fluid zone (advection-dispersion transient storage model or ADTS). A field test was performed on the flow through a single fracture that had been isolated by packers in the borehole. Water was injected into one borehole and withdrawn from another. The water contained a tracer for the first few hours of the test, and then water without the tracer was again injected. Figure 2.44 contains circles representing the field data, in terms of relative concentration, plotted versus elapsed time. Also shown on this figure are the results of a conventional advection-dispersion (AD) model and an advection-dispersion transient storage (ADTS) model. Both models matched the observed data for the first few hours of the test. However, the ADTS model was far superior in matching the field data over the entire course of the test. The effect of transient storage was to reduce the peak concentration and to increase the concentrations above what would be produced by advection-dispersion alone during the later periods of the test.

FIGURE 2.43 Zones of mobile and immobile water in a fracture.



Source: K. G. Raven, K. S. Novakowski, and P. A. Lapcevic. 1988. *Water Resources Research* 24:2019–2032. Copyright by the American Geophysical Union. Reproduced with permission.

FIGURE 2.44 Comparison of field data from a tracer test in fractured rock with results of model simulation using an advection-diffusion (AD) model and an advection-diffusion transient storage (ADTS) model.



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2.17 Summary

Solutes dissolved in groundwater are transported in two ways. Diffusion will cause solutes to move in the direction of the concentration gradient—that is, from areas of higher to lower concentration. This transport can occur even if the groundwater is not flowing and may be the major factor in mass transport in geologic materials of very low permeability.

Solutes are also transported by the process of advection. This occurs as the flowing groundwater carries the dissolved solutes with it. At the scale of a few pore diameters, groundwater will move parallel to the flow path at different rates due to differences in pore size. This causes the solute plume to spread along the direction of the flow path, a process called longitudinal dispersion. The solute plume will also spread laterally as flow paths diverge around mineral grains, a process known as transverse dispersion. At the laboratory column scale, the movement of a contaminant through a uniform porous media can be described by the advection-dispersion equation, which accounts for advection, diffusion, and porescale dispersion.

In field-scale studies it has been found that the coefficient of longitudinal dispersion obtained from the advection-dispersion equation increases with the length of the flow path. This is due to the heterogeneous nature of aquifer materials. As the length of the flow path increases, the range of permeability values that affect the rate of groundwater flow also increases. This causes the resulting solute plume to spread out more and more. This can be called macrodispersion. An apparent diffusion coefficient can be statistically correlated with the length of the flow path by the expression $\alpha_m = 0.83(\log L_s)^{2\times 414}$.

Stochastic methods of analysis have also been developed to analyze solute transport at the field scale. Stochastic methods are based on the variation in the hydraulic conductivity values because it is that variation that causes the solute plume to spread. The groundwater velocity depends upon the porosity as well as the hydraulic conductivity, but the hydraulic conductivity varies over a much greater range than porosity.

At the field scale the spreading due to hydraulic conductivity variation is much greater than that due to pore-scale dispersion. Both stochastic and advection-dispersion models demonstrate that the primary movement of the solute plume is due to advection. The stochastic model yields the movement of the center of mass of the solute plume from the average rate of movement of the groundwater. The variance of the solute concentration about the mean position, or the second spatial moment, is also obtained from stochastic models.

Chapter Notation

A	Cross-sectional area
a	Width of a fracture
b	Aquifer thickness
B	$[(v_x x)^2/(2D_L)^2 + (v_y y)^2/(4D_L D_T)]^{1/2}$
C	Solute concentration
C_i	Concentration at some point x and time t
C_0	Initial concentration, i.e. concentration at time 0
C_R	Dimensionless solute concentration (C/C_0)
$\langle C \rangle$	Ensemble mean concentration
c_a	Constant related to anisotropy
d	Characteristic flow length for Peclet number, P
dh/dl	Hydraulic gradient
D^*	Effective diffusion coefficient
D	Diffusion coefficient
D_d	Molecular diffusion coefficient
D_i	Coefficient of hydrodynamic dispersion in the i direction

D_L	Coefficient of longitudinal hydrodynamic dispersion
D_T	Coefficient of transverse hydrodynamic dispersion
E	Euler number (0-577…)
E_i	Exponential integral
f	Fractal dimension
F	Mass flux of solute per unit area per unit time
g	Acceleration of gravity
G	Topological dimension
h	Hydraulic head
H	Separation of autocorrelation function
i	Decay constant
I	Hydraulic gradient along a fracture
J	Constant length
k	Lag in autocorrelation function
K	Hydraulic conductivity
K_f	Equivalent hydraulic conductivity of a fracture
K_G	Geometric mean of hydraulic conductivity
K_0	Modified Bessel function of second kind and zero order
L	Straight-line distance between ends of a flowpath
L_e	Length of a tortuous flowpath
L_f	Length of a fractal flowpath
L_s	Straight-line length between ends of a fractal flowpath
M	Total mass of solute
N	Number of units
n	Porosity
n_e	Effective porosity
P_e	Peclet number ($v_x L / D_L$)
PV	Pore volume
Q	Rate at which a tracer is being injected into an aquifer
r	Radial distance to a well
R	Length of well screen or open borehole
R_f	Average frontal position of water injected into a well
r_Y	Autocorrelation of sampled values of Y
S_Y	Standard deviation of sampled values of Y
S_Y^2	Variance of sampled values of Y
t	Time
t'	Dimensionless time (tU / ϵ_h)
t_D	Dimensionless time $\left(\frac{V_x{}^2 t}{D_L}\right)$
t_R	Dimensionless time ($v_x t / L$)
T	Tortuosity
T_f	Fractal tortuosity
u	Average velocity of injection of water into a well
$\mathbf{u}$	Fluctuation in the velocity vector
u_{ij}	Covariance
$\mathbf{U}$	$\langle\mathbf{V}\rangle$ ensemble mean of velocity vectors
U_i	Total volume of water injected into a well
U_w	Cumulative volume of water withdrawn from a well
v_f	Velocity along a fractal flowpath
v_x	Average linear velocity in the x direction
V	Average fluid velocity in a fracture
$\mathbf{V}$	Velocity vector
$\langle\mathbf{V}\rangle$	Ensemble mean of the velocity vectors
$W[t, B]$	Hantush leaky well function
x	Coordinate vector
x_f	Length of fractal flowpath
(x_0, y_0)	Origin of an xy field
x_s	Straight-line distance
$\mathbf{X}'$	Residual of the displacement of a particle
$\langle\mathbf{X}\rangle$	Ensemble mean of the center of mass
$X_{ij}(t)$	Second spatial moment of the solute mass at time t and location j, l
$\mathbf{X}_t$	Total particle displacement
$\overline{Y}$	Mean of sample values of Y
Y_i	log K_i
Z_0	Constant related to a semivariogram
α	Dynamic dispersivity
α_L	Longitudinal dynamic dispersivity
α_T	Transverse dynamic dispersivity
α_a	Apparent dispersivity
β	Aperture of a fracture
ϵ_h	Correlation length for horizontal hydraulic conductivity

$\in_v$	Correlation length for vertical hydraulic conductivity
η	Fractal unit of measurement
η_c	Fractal cutoff limit
γ_Y	Semivariogram of Y
λ_Y	Correlation length of autocorrelation
μ	Viscosity of a fluid
$_Y$	Mean of population of Y
ν	Hurst coefficient for fractal dimensions
ω	Coefficient related to tortuosity
Ω	Anisotropy ratio ($\in_v/\in_h$)
ρ	Density of a fluid
ρ_Y	Autocorrelation of the population of Y
σ_Y	Standard deviation of population of Y
σ_Y^2	Variance of population of Y
τ	Fractional transverse position in a fracture
τ_Y	Autocovariance
θ	Angle in polar coordinate system
ξ	Fourier transform wave vector number
ζ	Fractional vertical position in a fracture

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6

Inorganic Chemicals in Groundwater

6.1 Introduction

Groundwater is a solvent that is in contact with various earth materials. As a result, groundwater naturally contains dissolved cations and anions as well as some nonionic inorganic material, such as silica (SiO_2). Naturally occurring groundwater can contain dissolved solids that range in concentration from less than 100 mg/L to more than 500,000 mg/L (Hem 1985). The major ion constituents of natural water include calcium, magnesium, sodium, potassium, chloride, sulfate, and bicarbonate/carbonate. Dissolved gasses can include nitrogen, carbon dioxide, methane, oxygen, and hydrogen sulfide. There are a number of ions that can be naturally present in small amounts that can affect the water quality. In addition, inorganic ions that impact upon water quality can be released to the subsurface via human activity. For example, at least 18 inorganic elements can be used in pesticides (chromium, chlorine, fluorine, tin, arsenic, selenium, barium, cadmium, sulfur, phosphorus, mercury, zinc, lead, copper, thallium, bismuth, boron, and antimony), and many metals can be joined with carbon to form organometalic pesticides (Clarkson 2001).

We have already seen in Chapter 3 that ions can be removed from solution by ion exchange and sorption. In this chapter we will examine other chemical processes that act to remove inorganic ions from solution. We will also examine the chemical properties of a number of inorganic materials frequently found in groundwater. The geochemical zonation that can occur near landfills that have received municipal waste will be used to illustrate some basic principles.

6.2 Units of Measurement and Concentration

Chemical analyses are usually reported on the basis of weight of solute per volume of solvent. Common units are **milligrams per liter** (mg/L) and **micrograms per liter** (μg/L). Equivalent weight units are frequently used when the chemical behavior of a solute is being considered. The **equivalent weight** of an ion is the formula weight divided by the electrical charge. If the concentration of the ion in milligrams per liter is divided by the formula weight, the resulting concentration is expressed in terms of **milliequivalents per liter**. One **mole** of a substance is its formula weight in grams. A 1-**molal** solution has 1 mole of solute in 1000 g of solvent. A 1-**molar** (1-*M*) solution has 1 mole of solute in a liter of solution.

If a solution is dilute and there is no need to make density corrections, the molality can be determined from the concentration by the following equation:

$$\text{Molality} = \frac{\text{milligrams per liter} \times 10^{-3}}{\text{formula weight in grams}} \quad \textbf{(6.1)}$$

6.3 Chemical Equilibrium and the Law of Mass Action

The law of mass action states that the rate of a chemical reaction will be proportional to the active masses of the participating substances (Hem 1985). If there are two substances, A and B, reacting to form two other substances, C and D, and if the process is reversible, then the reaction can be written as

$$a\text{A} + b\text{B} \rightleftharpoons c\text{C} + d\text{D} \quad \textbf{(6.2)}$$

The rate of the forward reaction, R_1, is

$$R_1 = k_1'[\text{A}]^a[\text{B}]^b \quad \textbf{(6.3)}$$

whereas the rate of the reverse reaction, R_2, is

$$R_2 = k_2'[\text{C}]^c[\text{D}]^d \quad \textbf{(6.4)}$$

where:

[A] = active concentration of substance A
k'_1 = proportionality constant for the forward reaction
k'_2 = proportionality constant for the reverse

If the reaction progresses to a point where the forward reaction rate is equal to the reverse reaction rate, then

$$k_1'[A]a[B]b \rightleftharpoons k_2'[C]c[D]d \quad \textbf{(6.5)}$$

Equation 6.5 can be rearranged to yield the following expression:

$$\frac{[C]^c[D]^d}{[A]^a[B]^b} = \frac{k_1'}{k_2'} = K_{eq} \quad \textbf{(6.6)}$$

where K_{eq} is the equilibrium constant.

If two or more ions react to form a solid precipitate and the reaction is reversible, then it can be represented as

$$a\text{A} + b\text{B} \rightleftharpoons c\text{AB} \quad \textbf{(6.7)}$$

The equilibrium relationship of this reaction is:

$$K_{sp} = \frac{[\text{A}]^a[\text{B}]^b}{[\text{AB}]^c} \quad \textbf{(6.8)}$$

where K_{sp} is called a **solubility product**. The activity of the solid together with the water is defined as unity. Solubility products can be used to compute the concentration of a solute in equilibrium with a solid phase, either via dissolution of the solid into an undersaturated solution or following precipitation of the solid from a saturated solution.

If one is dealing with a very dilute aqueous solution, then molal concentrations can be used to determine chemical equilibrium. However, for the general case, one must use **chemical activities** to employ the law of mass action.

The chemical activity of ion X, $[X]$, is equal to the molal concentration of X, m_x, times a factor known as an **activity coefficient**, γ_x:

$$[X] = m_x \gamma_x \qquad \textbf{(6.9)}$$

The activity coefficient varies with the total amount of cations and anions in solution. The concentration and charge of the various ions in a solution determine its **ionic strength**. Ionic strength can be computed from the following formula:

$$I = \frac{1}{2}\sum m_i z_i^2 \qquad \textbf{(6.10)}$$

where

I = ionic strength
m_i = molality of the ith ion
z_i = charge of the ith ion

Once the ionic strength is determined, the activity coefficient can be calculated using the Debye-Hückel equation:

$$-\log \gamma_i = \frac{A z_i^2 \sqrt{I}}{1 + a_i B \sqrt{I}} \qquad \textbf{(6.11)}$$

where

γ_i = the activity coefficient for ionic species i
z_i = the charge on ionic species i
I = ionic strength of the solution
A = constant equal to 0.5085 at 25°C
B = constant equal to 0.3281 at 25°C
a_i = the effective diameter of the ion from Table 6.1

The Debye-Hückel equation can be used with solutions that have an ionic strength of 0.1 or less (approximately 5000 mg/L). Figure 6.1 is a graph showing the relationship of activity coefficient to ionic strength for specific ions; it was calculated using the Debye-Hückel equation. Specific curves are for ions with the same effective diameter and charge as listed in Table 6.1. Not all the ions to which a curve applies are listed on the figure. For example, the curve labeled Ca^{2+} and Fe^{2+} can also be used for Cu^{2+}, Zn^{2+}, Sn^{2+}, Mn^{2+}, Ni^{2+}, and Co^{2+}, because all these ions have the same effective diameter and charge.

Chemical equilibrium is a useful concept in studies of contaminant hydrogeology. Ionic contaminants discharged into groundwater may react with naturally occurring of a solute in equilibrium with a solid phase, either via dissolution of the solid into an undersaturated solution or following precipitation of the solid from a saturated solution.

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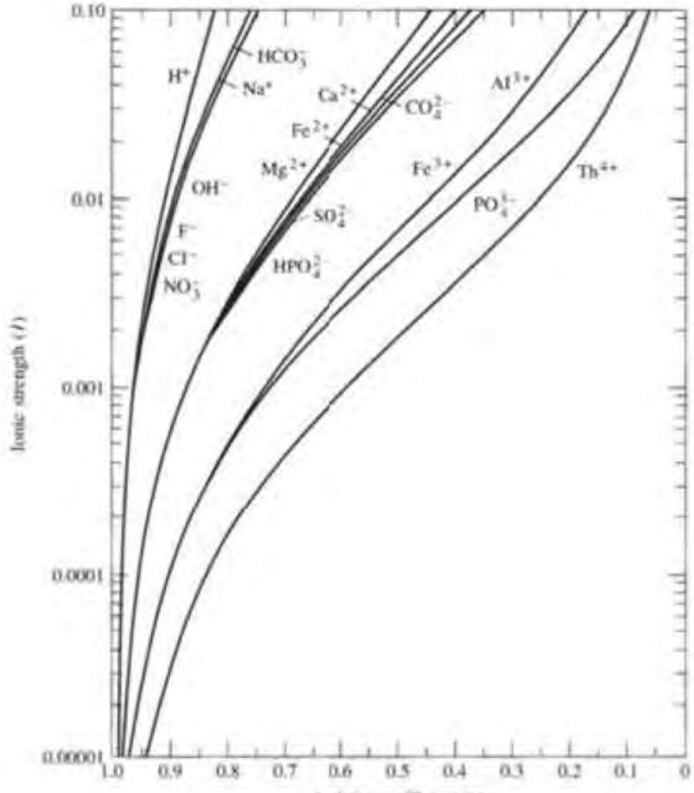
Chemical equilibrium is a useful concept in studies of contaminant hydrogeology. Ionic contaminants discharged into groundwater may react with naturally occurring

TABLE 6.1 Values of the parameter a_i in the Debye-Hückel equation.

a_i	Ion
11	Th^{4+}, Sn^{4+}
9	Al^{3+}, Fe^{3+}, Cr^{3+}, H^+
8	Mg^{2+}, Be^{2+}
6	Ca^{2+}, Cu^{2+}, Zn^{2+}, Sn^{2+}, Mn^{2+}, Fe^{2+}, Ni^{2+}, Co^{2+}, Li^+
5	$Fe(CN)_6{}^{4-}$, Sr^{2+}, Ba^{2+}, Cd^{2+}, Hg^{2+}, S^{2-}, Pb^{2+}, $CO_3{}^{2-}$, $SO_3{}^{2-}$, $MoO_4{}^{2-}$
4	$PO_4{}^{3-}$, $Fe(CN)_6{}^{3-}$, $Hg_2{}^{2-}$, $SO_4{}^{2-}$, $SeO_4{}^{2-}$, $CrO_4{}^{3-}$, $HPO_4{}^{2-}$, Na^+, $HCO_3{}^-$, $H_2PO_4{}^-$
3	OH^-, F^-, CNS^-, CNO^-, HS^-, $ClO_4{}^-$, K^+, Cl^-, Br^-, I^-, CN^-, $NO_2{}^-$, $NO_3{}^-$, Rb^+, Cs^+, $NH_4{}^+$, Ag^+

Source: J. Kielland. 1937. Individual activity coefficients of ions in aqueous solutions. *American Chemical Society Journal* 59:1676–1678. Published by the American Chemical Society. Used with permission.

FIGURE 6.1 Relationship of activity coefficients of dissolved ions as a function of the ionic strength of a solution at 25°C.



Source: J. D. Hem. 1985. *Study and interpretation of the chemical characteristics of natural waters.* Water Supply Paper 2254, U.S. Geological Survey.

ions in the groundwater to form a precipitate or they may mobilize ions sorbed on solid surfaces. They may also undergo oxidation or reduction. Both these processes are reversible and can be described by chemical equilibrium. Many geochemical processes in groundwater are not readily reversible, such as weathering of silicate minerals. These reactions must be treated using kinetics. However, as this type of reaction is not of significant interest in contaminant hydrogeology, we do not typically consider kinetic models.

Table 6.2 contains the solubility products for a large number of minerals, including many that can be formed from trace metals that can be ground-water contaminants.

6.4 Oxidation-Reduction Reactions

In some chemical reactions the participating elements change their valence state through the gain or loss of electron(s). If an electron is gained, there is a loss of positive valence called a reduction. A loss of negative valence is called an oxidation. Together, these are referred to as **oxidation-reduction**, or **redox**, reactions. In environmental systems they may be controlled by microorganisms that do not participate in the reaction but act as catalysts. The microbes occur as a biofilm on the surfaces of the aquifer materials. They obtain energy by oxidation of organic compounds or hydrogen or reduced inorganic forms of iron, nitrogen, and sulfur. Electron acceptors are necessary for these biologically mediated redox reactions to occur. Under aerobic conditions oxygen is the electron acceptor, whereas under anaerobic conditions nitrate, sulfate, and carbon dioxide are the electron acceptors (McCarty et al. 1984).

An example of a reduction is

$$Fe^{2+} + 2e^- \rightleftharpoons Fe^0 \tag{6.12}$$

In this example, ferrous iron is reduced to metallic iron by the addition of two electrons. This is a half-reaction, since the electrons must be supplied either by an electrical current or by a simultaneous reaction in which another element is oxidized and releases the requisite number of electrons. The standard electrical potential of a half-reaction is the voltage represented by the flow of electrons when the reaction is at equilibrium. Under standard conditions (25°C and 1 atm pressure) the standard potential is represented by the symbol E^0. The potential is in volts, with a negative value representing reducing conditions and a positive value representing oxidizing conditions (Hem 1985). By convention, the standard potential for the reduction of H^+ to hydrogen gas is 0:

$$2H^+ + 2e^- \rightleftharpoons H_2 \quad \text{(gas)} \tag{6.13}$$

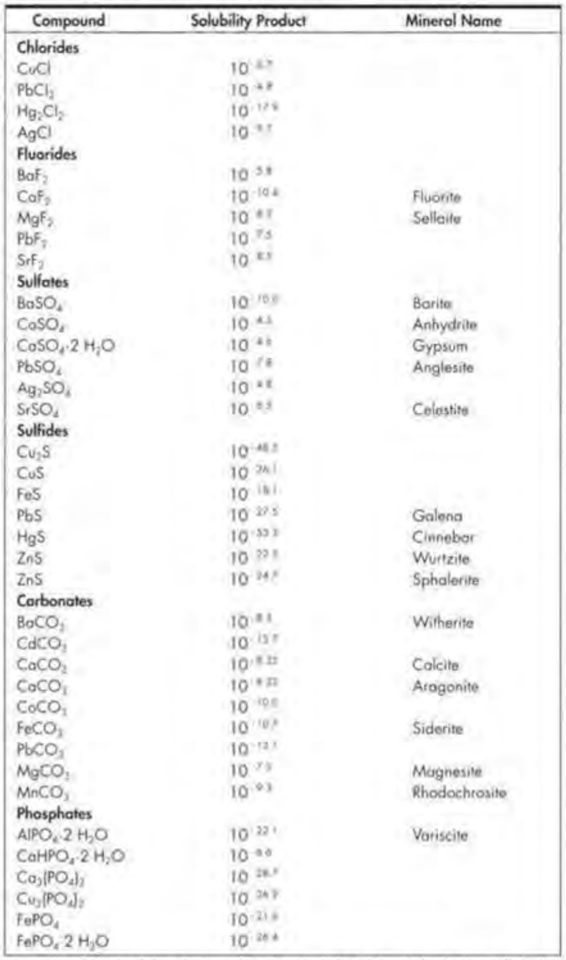
An example of oxidation occurs where ferrous iron loses an electron to form ferric iron:

$$Fe^{2+} \rightleftharpoons Fe^{3+} + e^- \tag{6.14}$$

Oxidation-reduction reactions involve elements that can occur in more than one valence state. In Equations 6.12 and 6.14, iron occurred in the metallic (0) as well as the +2 and +3 states. Metals can usually occur in the metallic state with a zero valence and at least one other valence state. Some elements that are environmentally important can occur in several different valence states. Table 6.3 lists several elements that occur in different valence states and examples of compounds and ions formed from those elements.

In order for oxidation or reduction to occur in a chemical reaction, one element must be reduced while a second element is being oxidized. For example, the complete equation for the oxidation of ferrous iron to ferric iron is

TABLE 6.2 Solubility products for selected minerals and compounds.



Compound	Solubility Product	Mineral Name
Chlorides		
CuCl	$10^{-6.7}$	
$PbCl_2$	$10^{-4.8}$	
Hg_2Cl_2	$10^{-17.9}$	
AgCl	$10^{-9.7}$	
Fluorides		
BaF_2	$10^{-5.8}$	
CaF_2	$10^{-10.4}$	Fluorite
MgF_2	$10^{-8.2}$	Sellaite
PbF_2	$10^{-7.5}$	
SrF_2	$10^{-8.5}$	
Sulfates		
$BaSO_4$	$10^{-10.0}$	Barite
$CaSO_4$	$10^{-4.5}$	Anhydrite
$CaSO_4 \cdot 2\ H_2O$	$10^{-4.6}$	Gypsum
$PbSO_4$	$10^{-7.8}$	Anglesite
Ag_2SO_4	$10^{-4.8}$	
$SrSO_4$	$10^{-6.5}$	Celestite
Sulfides		
Cu_2S	$10^{-48.5}$	
CuS	$10^{-36.1}$	
FeS	$10^{-18.1}$	
PbS	$10^{-27.5}$	Galena
HgS	$10^{-53.3}$	Cinnebar
ZnS	$10^{-22.5}$	Wurtzite
ZnS	$10^{-24.7}$	Sphalerite
Carbonates		
$BaCO_3$	$10^{-8.3}$	Witherite
$CdCO_3$	$10^{-13.7}$	
$CaCO_3$	$10^{-8.35}$	Calcite
$CaCO_3$	$10^{-8.22}$	Aragonite
$CoCO_3$	$10^{-10.0}$	
$FeCO_3$	$10^{-10.7}$	Siderite
$PbCO_3$	$10^{-13.1}$	
$MgCO_3$	$10^{-7.5}$	Magnesite
$MnCO_3$	$10^{-9.3}$	Rhodochrosite
Phosphates		
$AlPO_4 \cdot 2\ H_2O$	$10^{-22.1}$	Variscite
$CaHPO_4 \cdot 2\ H_2O$	$10^{-6.6}$	
$Ca_3(PO_4)_2$	$10^{-28.7}$	
$Cu_3(PO_4)_2$	$10^{-36.9}$	
$FePO_4$	$10^{-21.9}$	
$FePO_4 \cdot 2\ H_2O$	$10^{-26.4}$	

Source: K. B. Krauskopf, *Introduction to Geochemistry*, 2d ed. (New York: McGraw-Hill, 1979).

Source: K. B. Krauskopf. 1979. *Introduction to Geochemistry, Second Edition*. New York: McGraw-Hill.

TABLE 6.3 Selected elements that can exist in more than one oxidation state.

Element	Valence State	Examples
Carbon	+4	HCO_3^-, CO_3^{2-}
	0	C
	−4	CH_4
Chromium	+6	CrO_4^{2-}, $Cr_2O_7^{2-}$
	+3	Cr^{3+}, $Cr(OH)_3$
Copper	+1	CuCl
	+2	CuS
Mercury	+1	Hg_2Cl_2
	+2	HgS
Iron	+2	Fe^{2+}, FeS
	+3	Fe^{3+}, $Fe(OH)_3$
Nitrogen	+5	NO_3^-
	+3	NO_2^-
	0	N
	−3	NH_4^+, NH_3
Oxygen	0	O
	−1	H_2O_2
	−2	H_2O, O^{2-}
Sulfur	−2	H_2S, S^{2-}, PbS
	+2	$S_2O_3^{2-}$
	+5	$S_2O_6^{2-}$
	+6	SO_4^{2-}

$$4\,Fe^{2+} + O_2 + 4\,H^+ \rightleftharpoons 2\,H_2O + 4\,Fe^{3+} \tag{6.15}$$

This complete reaction is composed of two half-reactions:

$$4\,Fe^{2+} \rightleftharpoons 4\,Fe^{3+} + 4\,e^- \tag{6.16}$$

$$O_2 + 4\,H^+ + 4\,e^- \rightleftharpoons 2\,H_2O \tag{6.17}$$

An aqueous solution has an oxidation potential indicated by the symbol Eh. This can be calculated from the **Nernst equation**:

$$\mathrm{Eh} = E^0 - \frac{RT}{nF}\ln\frac{[\text{products}]}{[\text{reactants}]} \tag{6.18}$$

where:

Eh = oxidation potential of the aqueous solution in volts

E^0 = standard potential of redox reaction in volts

R = gas constant, 0.00199 Kcal/(mole·K)

T = temperature in Kelvins

F = Faraday constant, 23.06 Kcal/V

n = number of electrons in half-reaction

[ ] = activity of products and reactants

The standard potential for a reaction can be determined from the relationship

$$E^0 = \frac{-\Delta G_R^0}{nF} \tag{6.19}$$

where ΔG_R^0 in volts is the **free energy**, or **Gibbs free energy**, of the reaction.

The free energy of a reaction is the sum of the free energies of the products minus the sum of the free energies of the reactants. For the reaction

$$a\mathrm{A} + b\mathrm{B} \rightleftharpoons c\mathrm{C} + d\mathrm{D}$$

the free energy can be found from:

$$\Delta G_R^0 = c\Delta G_c^0 + d\Delta G_d^0 - a\Delta G_a^0 - b\Delta G_b^0 \tag{6.20}$$

Values of free energy for many elements, ions, and compounds are found in standard reference works. Table 6.4 contains values for a number of species.

The equilibrium constant for a reaction is related to the free energy of the reaction by

$$\Delta G_R^0 = -RT \ln K_{eq} \tag{6.21}$$

At standard temperature and pressure and with ΔG_R^0 in kilocalories, Equation 6.21 can be rewritten as

$$\log K_{eq} = \frac{-\Delta G_R^0}{1.364} \tag{6.22}$$

The oxidation potential of an aqueous solution can be measured using a redox or ORP electrode. If the value is positive, the solution is oxidizing, and if it is negative, the solution is reducing. Oxidation potential is measured in volts relative to the hydrogen electrode, which is at zero. Commercially available Eh meters are available that can be attached to a groundwater sampling pump. The groundwater sample is pumped under positive pressure into the flowthrough cell where the electrode is located. The water sample is never subjected to a vacuum, which could cause degassing. Moreover, it is not exposed to the atmosphere, where it can come into contact with atmospheric oxygen. This has simplified the accurate and precise measurement of Eh in groundwater. Eh is directly proportional to pE, which is defined as the logarithm of the electron concentration in a solution, and is an analogous measure of the **oxidation/reduction potential**, ORP.

6.5 Relationship between pH and Eh

6.5.1 pH

Water undergoes a dissociation into two ionic species:

$$\mathrm{H_2O} \rightleftharpoons \mathrm{H^+} + \mathrm{OH^-} \tag{6.23}$$

The equilibrium constant for this reaction is

$$K_{eq} = \frac{[\mathrm{H^+}][\mathrm{OH^-}]}{[\mathrm{H_2O}]} \tag{6.24}$$

TABLE 6.4 Standard Gibbs free energy of formation for selected species.

Species	ΔG° kcal/mole	Species	ΔG° kcal/mole	Species	ΔG° kcal/mole
Arsenic		**Manganese**		UO_2(c) (uranite)	−246.61[e]
As_2O_5(c)	−187.0[a]	MnO_2(c) (pyrolusite)	−111.18[b]	UO_2^{+}(aq)	−229.69[e]
As_4O_6(c)	−275.46[a]	Mn_2O_3 (bixbyite)	−210.6[b]	UO_2^{2+} (aq)	−227.68[e]
As_2S_3(c)	−40.3[a]	Mn_3O_4 (hausmannite)	−306.7[b]	$(UO_2)_2(OH)_2^{2+}$(aq)	−560.99[e]
$FeAsO_4$(c)	−185.13[a]	$Mn(OH)_2$ (c) amorphous	−147.0[b]	$(UO_2)_3(OH)_5^{+}$ (aq)	−945.16[e]
H_3AsO_4(aq)	−183.1[a]	$MnCO_3$(c) (rhodochrosite)	−195.2[b]	$(UO_2)_3(OH)_7^{-}$	−1037.5[e]
$H_2AsO_4^{-}$(aq)	−180.04[a]	Mn^{2+}(aq)	−54.5[b]	$UO_2CO_3^{0}$(c)	−367.07[e]
$HAsO_4^{2-}$ (aq)	170.82[a]	$MnOH^{+}$(aq)	−96.8[b]	$UO_2(CO_3)_2^{2-}$(aq)	−503.2[e]
AsO_4^{3-}(aq)	−155.0[a]	**Molybdenum**		$UO_2(CO_3)_3^{4-}$(aq)	−635.69[e]
$HAsO_2$(aq)	−96.25[a]	MoO_3(c)	−159.66[b]	**Miscellaneous species**	
AsO_2^{-} (aq)	−83.66[a]	MoO_2(c)	−127.40[b]	$ZnFe_2O_4$(c)	−254.2[a]
Chromium		$FeMoO_4$(c)	−233[b]	$CuFeO_2$(c)	−114.7[b]
Cr_2O_3(c)	−252.9[f]	MoO_4^{2-} (aq)	−199.9[b]	$CuFe_2O_4$(c)	−205.26[b]
$HCrO_4^{-}$	−182.8[f]	**Silver**		$NiFe_2O_4$(c)	−232.6[b]
$Cr_2O_7^{2-}$(aq)	−311.0[f]	Ag_2O(c)	−2.68[b]	H_2O(l)	−56.687[a]
CrO_4^{2-} (aq)	−173.96[f]	AgCl(c)	−26.24[b]	OH^{-}(aq)	−37.594[a]
Copper		Ag_2S(c)	−9.72[b]	O_2(aq)	−3.9[a]
CuO(c)	−31.0[b]	Ag_2CO_3(c)	−104.4[b]	HSO_4^{-}(aq)	−180.69[a]
$CuSO_4 \cdot 3Cu(OH)_2$(c)	−434.5[b]	Ag^{+}(aq)	18.43[b]	SO_4^{2-} (aq)	−177.97[a]
(brochantite)		AgOH(aq)	−22.0[b]	H_2S(aq)	−6.66[a]
Cu_2O(c)	−34.9[b]	$Ag(OH)_2^{-}$(aq)	−62.2[b]	HS^{-}(aq)	2.88[a]
Cu_2S(c)	−20.6[b]	AgCl(aq)	−17.4[b]	S^{2-}(aq)	20.5[a]
Cu^{2+}(aq)	15.67[b]	$AgCl_2^{-}$(aq)	−51.5[b]	CO_2(g)	−94.254[a]
$CuSO_4$(aq)	−165.45[b]	**Vanadium**		CO_2(aq)	−92.26[a]
$HCuO_2^{-}$(aq)	−61.8[b]	$H_4VO_4^{+}$	−253.67[k]	H_2CO_3(aq)	−148.94[a]
CuO_2^{2-}(aq)	−43.9[b]	$H_3VO_4^{0}$	−249.2[k]	HCO_3^{-} (aq)	−140.26[a]
Cu^{+}(aq)	11.95[b]	$H_2VO_4^{-}$	−244[k]	CO_3^{2-} (aq)	−126.17[a]
Iron		HVO_4^{2-}(aq)	−233.0[i]	Cl^{-}(aq)	−31.37[a]
$Fe(OH)_3$(c) ppt.	−166.0[h]	VO_4^{3-}(aq)	−214.9[k]	CH_4(g)	−12.13[a]
$Fe(OH)_2$(c) ppt.	−116.3[f]	VO^{2+}(aq)	−106.7[i]	CH_4(aq)	−8.22[a]
$FeCO_3$(c) (siderite)	−159.35[h]	$V(OH)_3^{0}$(aq)	−212.9[k]	H^{+}(aq)	0.00
FeS_2(c) (pyrite)	−39.9[b]	VOH^{2+}(aq)	−111.41[k]	Cl^{-}(aq)	−31.38[c]
Fe_2O_3 (hematite)	−177.4[b]	$V(OH)_2^{+}$	−163.2[k]	PO_4^{3-} (aq)	−243.5[a]
Fe^{3+}(aq)	−1.1[b]	$VOOH^{+}$	−155.65[k]	HPO_4^{2-} (aq)	−260.34[a]
$FeOH^{2+}$(aq)	−54.83[b]	V^{3+}	−57.8[k]	$H_2PO_4^{-}$ (aq)	−270.14[k]
$Fe(OH)_2^{+}$(aq)	−106.7[i]	**Uranium**		$H_3PO_4^{0}$(c)	−273.10[a]
Fe^{2+}(aq)	−18.85[b]	U^{4+}(aq)	−126.44[e]	Na^{+}(aq)	−62.59[c]
$FeOH^{+}$(aq)	−62.58[i]	UOH^{3+}(aq)	−182.24[e]	K^{+}(aq)	−67.51[c]
$Fe(OH)_3^{-}$(aq)	−147.0[b]	$U(OH)_4^{0}$(c)	−347.18[e]	NH_4^{+}(aq)	−18.99[c]
$Fe(OH)_4^{-}$(aq)	−198.4[i]			Pb^{2+}(aq)	−5.83[a]
FeO(c)	−60.03[g]			O_2(g)	0.00
Fe_2S(c) (pyrite)	−38.3[g]				
FeS(c)	−24.22[g]				

c = solid
aq = aqueous solutions
g = gas

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[a] Wageman, D. D., W. H. Evans, V. B. Parker, 1. Halow, S. M. Baily, and R. H. Schumm. 1968. *Selected values of chemical thermodynamic properties.* National Bureau of Standards Technical Note 270–3; 264 pp.

[b] Wageman, D. D., W. H. Evans, V. B. Parker, 1. Halow, S. M. Baily, and R. H. Schumm. 1969. *Selected values of chemical thermodynamic properties.* National Bureau of Standards Technical Note 270–4; 141 pp.

(*Cont'd*)

TABLE 6.4 *Cont't*

[c] CODATA Task Group on Key Values for Thermodynamics. 1976. Recommended key values for thermodynamics 1975. *Journal of Chemical Thermodynamics* 8:603–5.

[d] CODATA Task Group on Key Values for Themodynamics. 1977. Recommended key values for thermodynamics 1976. *Journal of Chemical Thermodynamics* 9:705–6.

[e] Giridhar J., and Donald Langmuir. 1991. Determination of E° for the UO_2^{2+}/U^{4+} couple from measurement of the equilibrium: $UO_2^{2+} + Cu(s) + 4\ H^+ = U^{4+} + Cu\ 2^+ + 2\ H_2O$ at 25°C and some geochemical implications. *Rodiochemica Acta* 54: 133–38.

[f] *Handbook of Chemistry and Physics.* Selected Values of Chemical Thermodynamic Properties. Boca Raton, Fla.: CRC Press.

[g] Robie, R. A., B. S. Hemingway, and J. R. Fisher. 1978. *Thermodynamic properties of minerals and related substances* at 298.15 K *and* 1 bar (105 *pascals) pressure and higher temperatures.* U. S. Geological Survey Bulletin 1452; 456 pp.

[h] Feitknecht, Walter, and P. W. Schindler. 1963. Solubility constants of metal oxides, metal hydroxides and metal salts in aqueous solution. *Pure and applied Chemistry* 6: 130–57.

[i] Baes, C. F., Jr., and R. E. Messmer. 1976. *The Hydrolysis of Cations.* New York: Wiley, 489 pp.

[j] Wageman, D. D., W. H. Evans, V. B. Parker, 1. Halow, S. M. Baily, and R. H. Schumm. 1968. *Selected values of chemical thermodynamic properties.* National Bureau of Standards Technical Note 270–5.

[k] Langmuir, Donald. 1977. Uranium solution mineral equilibria at low temperatures. *Geochimica et Cosmochimica Acta* 42:547–69.

The value of this equilibrium constant depends upon the temperature, but at 25°C it is 1×10^{-14}. Water that is neutral has the same number of H^+ and OH^- ions. If there are more H^+ ions, water is acidic, and if there are more OH^- ions, it is basic.

The pH of an aqueous solution is a measure of the number of hydrogen ions or protons present. The definition of pH is the negative logarithm of the hydrogenion activity. It ranges from 0 (most acidic) to 14 (most basic), and at 25°C a pH of 7 means that the solution is neutral. Because $[H_2O]$ is unity, from Equation 6.24 we have the relationship $[H^+][OH^-] = K_{eq} = 10^{-14}$. The pH of a solution is measured with a pH meter and an electrode. It should be measured in the field, preferably in a flowthrough cell so that dissolved gas isn't exchanged with the atmosphere prior to the measurement. The pH of a solution is especially sensitive to the amount of dissolved CO_2.

6.5.2 Relationship of Eh and pH

We thus have two ways to characterize a solution. The pH describes the number of protons present and the Eh is related to the number of electrons. Eh and pH can be related through the Nernst equation for a reaction that contains water and H^+ ions. Such a reaction can be written (Robertson 1975)

$$bB + mH^+ + ne^- \rightleftharpoons aA + wH_2O \qquad \textbf{(6.25)}$$

where

A = reactant
B = product
n = number of electrons released
a = moles of reactant
w = moles of water
b = moles of product
m = moles of hydrogen ions

The Nernst equation for Reaction 6.25 is

$$\mathrm{Eh} = E^{\circ} - \frac{RT}{nF}\ln\frac{[\mathrm{A}]^a[\mathrm{H_2O}]^w}{[\mathrm{B}]^b[\mathrm{H^+}]^m} \tag{6.26}$$

The activity of water is unity. For a particular reaction, E° is given and R, T, and F are constants. The significant variables are the Eh and the activities of the reactant, the product, and the hydrogen-ion activity, which can be expressed as a pH. Equation 6.26 can be rearranged and expressed in base 10 logs as either

$$\mathrm{Eh} = E^{\circ} - 2.303\frac{RT}{nF}\log\frac{[\mathrm{A}]^a}{[\mathrm{B}]^b[\mathrm{H^+}]^m} \tag{6.27}$$

or

$$\mathrm{Eh} = E^{\circ} - 2.303\frac{RT}{nF}\log\frac{[\mathrm{A}]^a}{[\mathrm{B}]^b} + 2.303\frac{RTm}{nF}\log[\mathrm{H^+}] \tag{6.28}$$

At 25°C and 1 atm of pressure, Equation 6.28 can be expressed as

$$\mathrm{Eh} = E^{\circ} - \frac{0.0592}{n}\log\frac{[\mathrm{A}]^a}{[\mathrm{B}]^b} - 0.0592\frac{m}{n}\mathrm{pH} \tag{6.29}$$

6.5.3 Eh-pH Diagrams

The Eh-pH relationship is particularly useful when applied in the form of an Eh-pH diagram, with Eh the ordinate and pH the abscissa. If a solution has several ions present that can react to form different products or occur in different valence states, the stable product or valence state at a given concentration of reactants will be a function of the pH and Eh of the solution.

Figure 6.2 is a basic Eh-pH diagram. The range of pH is 0 to 14. For Eh, it is convenient to specify a range of about +1.4 to −1.0 V. In certain regions of the Eh-pH field, water will be oxidized to O_2, and in other regions water will be reduced to H_2. We will calculate these regions as an example problem.

EXAMPLE PROBLEM

Calculate the stability field for water at standard conditions.

The oxidation of water is given by

$$O_2(g) + 4H^+ + 4e^- \rightleftharpoons 2H_2O(l)$$

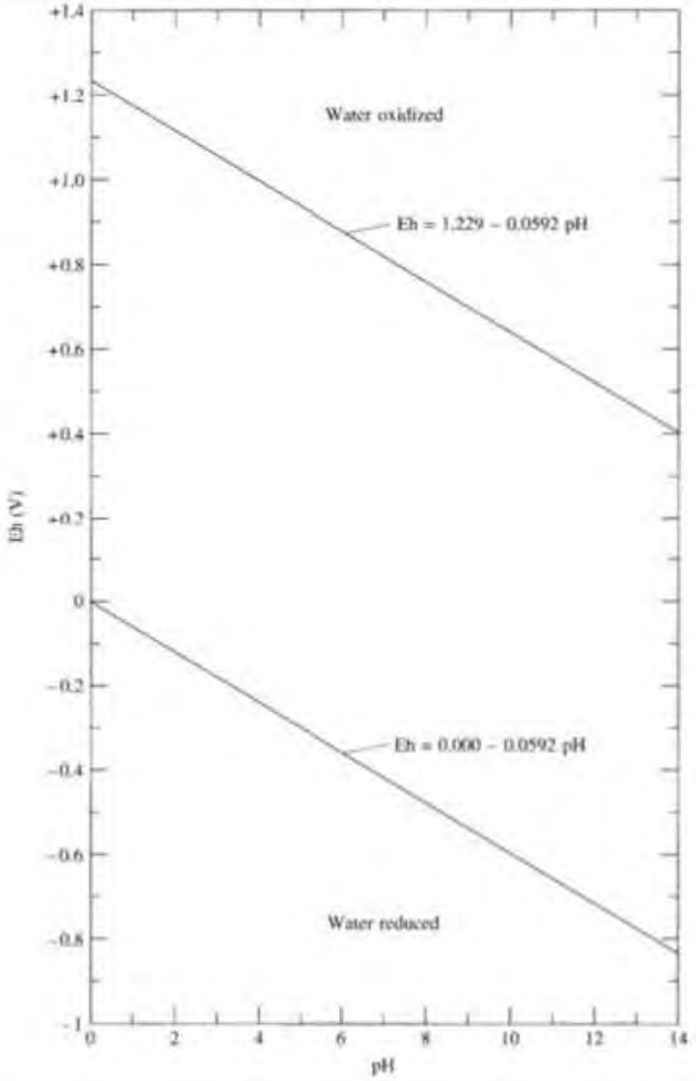
From Table 6.4,

$$\Delta G^0_{\mathrm{H_2O}(l)} = -56.69 \text{ kcal}$$

$$\Delta G^0_{\mathrm{O_2}(g)} = 0$$

$$\Delta G^0_{H^+} = 0$$

FIGURE 6.2 Eh-pH diagram showing the stability field for water.



From Equation 6.20,

$$\Delta G_R^0 = 2\Delta G_{H_2O(l)}^0 - \Delta G_{O_2(g)}^0 - 4\Delta G_{H^+}^0$$

$$\Delta G_R^0 = 2(-56.69) - 0 - 4(0) = -113.38\ kcal$$

The value of ΔG_R^0 in kilocalories is converted to a standard potential by use of Equation 6.19:

$$E^0 = \frac{-\Delta G_R^0}{nF} = \frac{-(-113.38)}{4 \cdot 23.06} = 1.229\ \text{V}$$

The Nernst equation (Equation 6.24) can be expressed as:

$$\text{Eh} = E^0 - \frac{RT}{nF} 2.303 \log \frac{[H_2O]}{[O_2][H^+]^4}$$

The activity of dissolved gaseous oxygen is expressed as a partial pressure, P_{o2}. At standard conditions it has a value of 1atm. The activity of water is unity. The Nernst equation thus reduces to

$$\mathrm{Eh} = 1.229 - \frac{0.00199 \cdot 298}{4 \cdot 23.06} 2.303 \log \left[\mathrm{H}^{+}\right]^{-4}$$

This expression can be reduced to

$$\mathrm{Eh}_{(\mathrm{Volts})} = 1.229 - 0.0592\mathrm{pH}$$

This equation defines the upper boundary of stability for water, above which oxidation would break apart the water molecule.

The reduction of hydrogen ions to form gaseous hydrogen is

$$2\mathrm{H}^{+} + 2\mathrm{e}^{-} \rightleftharpoons \mathrm{H}_{2(\mathrm{gas})}$$

From Table 6.4,

$$\Delta G^{0}_{H^{+}} = 0$$

$$\Delta G^{0}_{H_2(\mathrm{gas})} = 0$$

The value of ΔG^{0}_{R} for the formation of hydrogen gas is obviously zero. Therefore, the value of E^0 is also zero.

From the Nernst equation,

$$\mathrm{Eh} = E^{0} - \frac{0.00199 \cdot 298}{2 \cdot 23.06} 2.303 \log \frac{p_{H_2}}{\left[\mathrm{H}^{+}\right]^{2}}$$

The value of P_{H2} is 1 atm and the calculated value of E^0 is 0, hence the preceding expression can be reduced to

$$\mathrm{Eh}_{(\mathrm{volts})} = 0.000 - 0.0592\mathrm{pH}$$

This equation forms the lower boundary of the stability field for water. These boundaries are plotted in Figure 6.2.

6.5.4 Calculating Eh-pH Stability Fields

The stability fields within the Eh-pH diagram for various forms of an element can be computed using chemical thermodynamics. Basic sources of thermodynamic data include Bagman et al. (1968; 1969; 1971) and Robie et al. (1978).

Boundaries for an element between dissolved species that have different valence states are computed using the Nernst equation (Equation 6.27, 6.28, or 6.29). If both ions are at the same valence state, then the equation for chemical equilibrium is used. If one is calculating the boundary between a solid species and a dissolved form, the chemical activity of the solid species is 1. For some of the boundaries of solid species, it will be necessary to assume an activity for the dissolved species.

EXAMPLE PROBLEM

Calculate an Eh-pH diagram for iron in which the solid species are $Fe(OH)_3$ and FeO and the activity of dissolved iron is 56 µg/L(10^{-6} M).

Soluble forms of the ferrous ion and the ferric ion include Fe2$^+$, Fe3$^+$, FeOH2$^+$, and $Fe(OH)_2^+$. Transformations between these ions are determined by redox equations:

$$\mathrm{FeOH^{2+} + H^+ + e^- \rightleftharpoons Fe^{2+} + H_2O} \tag{6.30}$$

$$\mathrm{Fe(OH)_2^+ + H^+ + e^- \rightleftharpoons Fe^{2+} + 2H_2O} \tag{6.31}$$

$$\mathrm{Fe^{3+} + e^- \rightleftharpoons Fe^{2+}} \tag{6.32}$$

The free energy and the standard potential for these reactions can be determined from Equations 6.20 and 6.19, respectively.

From Table 6.4 free energies are as follows.

$$\mathrm{FeOH^{2+}} = -54.83\ \text{kcal/mol}$$

$$\mathrm{Fe(OH)_2^+} = -106.7\ \text{kcal/mol}$$

$$\mathrm{Fe^{2+}} = -18.85\ \text{kcal/mol}$$

$$\mathrm{Fe^{3+}} = -1.1\ \text{kcal/mol}$$

$$\mathrm{H_2O} = -56.69\ \text{kcal/mol}$$

$$\mathrm{FeO} = -60.03\ \text{kcal/mol}$$

$$\mathrm{Fe(OH)_3} = -166\ \text{kcal/mol}$$

$$\mathrm{Fe(OH)_4^-} = -198.4\ \text{kcal/mol}$$

$$\mathrm{H^+} = 0$$

For Reaction 6.30 ($FeOH^{2+} + H^+ + e^- \rightleftharpoons Fe2^+ + H_2O$):

$$\Delta G_R^0 = \left[\Delta G_{H_2O}^0 + \Delta G_{Fe^{2+}}^0\right] - \left[\Delta G_{FeOH^{2+}} + \Delta G_{H^+}^0\right]$$

$$\Delta G_R^0 = -56.69 + (-18.85) - (-54.83) - 0$$

$$\Delta G_R^0 = -20.71\text{kcal/mol}$$

$$E^0 = \frac{-\Delta G^0{}_R}{nF} = \frac{-(-20.71)}{1 \cdot 23.06}\text{V}$$

$$E^0 = +0.898\text{ V}$$

For Reaction 6.31 ($Fe(OH)_2^+ + 2H^+ + e^- \rightleftharpoons Fe^{2+} + 2H_2O$):

$$\Delta G_R^0 = 2\Delta G_{H_2O}^0 + \Delta G_{Fe^{2+}}^0 - \Delta G_{Fe(OH)_2+}^0 - 2\Delta G_{H^+}^0$$

$$\Delta G_R^0 = 2(-56.69) + (-18.85) - (-106.7) - 2(0)$$

$$\Delta G_R^0 = -25.53\text{kcal/mol}$$

$$E^0 \frac{-\Delta G_R^0}{nF} = \frac{-(-25.53)}{1 \cdot 23.06}\text{V}$$

$$E^0 = +1.107\text{V}$$

For Reaction 6.32 ($Fe3^{+} + e^{-} \rightleftharpoons Fe^{2+}$):

$$\Delta G_R^0 = \Delta G_{Fe^{2+}}^0 - \Delta G_{Fe^{3+}}^0$$

$$\Delta G_R^0 = -18.85 - (-1.1)$$

$$\Delta G_R^0 = -17.75$$

$$E^0 = \frac{-\Delta G_R^0}{nF} = \frac{-(-17.75)}{1 \cdot 23.06} V$$

$$E^0 = +0.770 V$$

The boundaries between the stability fields are determined from the Nernst equation. At the boundary between two fields, the activities of the iron species on the left of the reaction is equal to the activity of the iron species on the right of the equation—i.e., the two species are at equilibrium.

For Reaction 6.30 ($FeOH^{2+} + H^{+} + e^{-} \rightleftharpoons Fe^{2+} + H_2O$):

$$Eh = E^0 - \frac{0.0592}{n} \log \frac{[Fe^{2+}]}{[FeOH^{2+}]} - 0.0592 \frac{m}{n} pH$$

Since $[FeOH^{2+}] = [Fe^{2+}]$, m (the number of hydrogen ions) = 1, n(the number of electrons) = 1, $E^0 = +0.898$ V, and log 1 = 0:

$$Eh_{(volts)} = 0.898 - 0.0592\ pH \qquad \textbf{(6.33)}$$

For Reaction 6.31 ($Fe(OH)_2^{\ +} + 2H^{+} + e^{-} \rightleftharpoons Fe^{2+} + 2H_2O$):

$$Eh = E^0 - \frac{0.0592}{n} \log \frac{[Fe^{2+}]}{[Fe(OH)_2^{\ +}]} - 0.0592 \frac{m}{n} pH$$

Since $[Fe(OH)_2^{\ +}] = [Fe^{2+}]$, $m = 2$, $n = 1$, and $E^0 = +1.107$ V:

$$Eh_{(volts)} = 1.107 - 0.1184\ pH \qquad \textbf{(6.34)}$$

For Reaction 6.32 ($Fe^{3+} + e^{-} \rightleftharpoons Fe^{2+}$):

$$Eh = E^0 - \frac{0.0592}{n} \log \frac{[Fe^{2+}]}{[Fe^{3+}]} - 0.0592 \frac{m}{n} pH$$

This reaction is independent of pH because neither $[H^+]$ nor $[OH^-]$ appears in the reaction. Hence the value of m is 0. Because as $[Fe^{3+}] = [Fe^{2+}]$ and log 1= 0, Eh is a constant equal to E^0, which is 0.770 V:

$$Eh = 0.770\ V \qquad \textbf{(6.35)}$$

The boundary between two dissolved species that are at the same valence state can be determined from chemical equilibrium.

For iron there are two boundaries between dissolved ions of ferric iron. These boundaries are represented by these reactions:

$$\mathrm{Fe}^{3+} + \mathrm{H}_2\mathrm{O} \rightleftharpoons \mathrm{FeOH}^{2+} + \mathrm{H}^+ \tag{6.36}$$

$$\mathrm{FeOH}^{2+} + \mathrm{H}_2\mathrm{O} \rightleftharpoons \mathrm{Fe(OH)_2}^+ + \mathrm{H}^+ \tag{6.37}$$

For Reaction 6.36 $\left(\mathrm{Fe}^{3+} + \mathrm{H}_2\mathrm{O} \rightleftharpoons \mathrm{FeOH}^{2+} + \mathrm{H}^+\right)$, the equilibrium constant can be obtained from the free energy of the reaction. The first step is to find the free energy of the reaction using Equation 6.20.

$$\Delta G_R^0 = \Delta G^0_{\mathrm{FeOH}^{2+}} + \Delta G^0_{\mathrm{H+}} - \Delta G^0_{\mathrm{Fe}^{3+}} - \Delta G^0_{\mathrm{H_2O}}$$

$$\Delta G_R^0 = -54.83 + 0 - (-1.1) - (-56.69)$$

$$\Delta G_R^0 = +2.96 \text{ kcal/mol}$$

The next step is to determine the equilibrium constant using Equation 6.22.

$$\log k_{eq} = -\frac{\Delta G_R^0}{1.364} = -\frac{2.96}{1.364} = -2.17$$

$$K_{eq} = 10^{-2.17}$$

From Equation 6.6,

$$K_{eq} = \frac{\left[\mathrm{FeOH}^{2+}\right]\left[\mathrm{H}^+\right]}{\left[\mathrm{Fe}^{3+}\right]\left[\mathrm{H_2O}\right]} = 10^{-2.17}$$

Since $[\mathrm{H_2O}] = 1$ and at the boundary $[\mathrm{FeOH}^{2+}] = [\mathrm{Fe}^{3+}]$,

$$[\mathrm{H}^+] = 10^{-2.17} \tag{6.38}$$

This means that a vertical line at a pH of 2.17 separates these two stability fields.

For Reaction 6.37 $\left(\mathrm{FeOH}^{2+} + \mathrm{H}_2\mathrm{O} \rightleftharpoons \mathrm{Fe(OH)_2}^+ + \mathrm{H}^+\right)$, find the free energy of the reaction:

$$\Delta G_R^0 = \Delta G^0_{\mathrm{Fe(OH)_2}^+} + \Delta G^0_{\mathrm{H+}} - \Delta G^0_{\mathrm{FeOH}^{2+}} - \Delta G^0_{\mathrm{H_2O}}$$

$$\Delta G_R^0 = -106.7 + 0 - (-54.83) - (-56.69)$$

$$\Delta G_R^0 = +4.82 \text{ kcal/mol}$$

Next find the value of K_{eq}:

$$\log K_{eq} = \frac{-\Delta G_R^0}{1.364} = \frac{-4.82}{1.364} = -3.53$$

$$K_{eq} = 10^{-3.53}$$

Finally, from Equation 6.6,

$$K_{eq} = \frac{\left[\mathrm{Fe(OH)}^{2+}\right]\left[\mathrm{H}^+\right]}{\left[\mathrm{FeOH}^{2+}\right]\left[\mathrm{H_2O}\right]} = 10^{-3.53}$$

Since $[H_2O] = 1$ and $[Fe(OH)^{2+}] = [FeOH^{2+}]$,

$$[\mathrm{H}^+] = 10^{-3.53} \tag{6.39}$$

Lines that delineate the stability field for solids can be obtained by similar reasoning. Remember that the activity of a solid in equilibrium with dissolved species is 1. The location of the boundaries of solid species is a function of the amount of dissolved iron present.

In this situation there are two stable iron precipitates, Fe(OH)3 and FeO. The reactions at the boundaries include

$$\mathrm{Fe(OH)_3 + H^+ \rightleftharpoons Fe(OH)_2{}^+ + H_2O} \tag{6.40}$$

$$\mathrm{Fe(OH)_3 + 3H^+ + e^- \rightleftharpoons Fe^{2+} + 3H_2O} \tag{6.41}$$

$$\mathrm{Fe(OH)_4{}^- + H^+ \rightleftharpoons Fe(OH)_3 + H_2O} \tag{6.42}$$

$$\mathrm{Fe(OH)_3 + e^- \rightleftharpoons FeO + H_2O + OH^-} \tag{6.43}$$

$$\mathrm{Fe(OH)_4{}^- + 2H^+ + e^- \rightleftharpoons FeO + 3H_2O} \tag{6.44}$$

$$\mathrm{FeO + 2H^+ \rightleftharpoons Fe^{2+} + H_2O} \tag{6.45}$$

Reaction 6.40 $\mathrm{Fe(OH)_3 + H^+ \rightleftharpoons Fe(OH)_2{}^+ + H_2O}$ is solved using an equilibrium approach:

$$\Delta G_R^0 = \Delta G^0_{\mathrm{Fe(OH)_2{}^+}} + \Delta G^0_{\mathrm{H_2O}} - \Delta G^0_{\mathrm{Fe(OH)_3}} - \Delta G^0_{\mathrm{H^+}}$$

$$\Delta G_R^0 = -106.7 + (-56.69) - (-166) - 0 = 2.61$$

$$\log K_{eq} = -\frac{\Delta G_R^0}{1.364} = -\frac{2.61}{1.364} = -1.91$$

$$K_{eq} = 10^{-1.91}$$

$$K_{eq} = \frac{\left[\mathrm{Fe(OH)_2{}^+}\right]\left[\mathrm{H_2O}\right]}{\left[\mathrm{Fe(OH)_3}\right]\left[\mathrm{H^+}\right]} = 10^{-1.91}$$

Since [Fe(OH)3] = 1and [H2O] = 1,

$$\left[H^+\right]=\frac{\left[Fe(OH)_2{}^+\right]}{10^{-1.91}}$$

Reaction 6.41 $Fe(OH)_3+3H^++e^-\rightleftharpoons Fe^{2+}+3H_2O$ is solved using the Nernst equation:

$$\Delta G_R^0=\Delta G_{Fe^{2+}}^0+3\Delta G_{H_2O}^0-\Delta G_{Fe(OH)_3}^0-3\Delta G_{H^+}^0$$

$$\Delta G_R^0=-18.85+3(-56.69)-(-166)-0$$

$$\Delta G_R^0=-22.95\ \text{kcal/mol}$$

$$E^0=\frac{-\Delta G_R^0}{nF}=-\frac{(-22.95)}{1\cdot 23.06}=+0.994\text{V}$$

$$Eh=E^0-\frac{0.0592}{n}\log\frac{\left[Fe^{2+}\right]}{\left[Fe(OH)_3\right]}-0.0592\frac{m}{n}pH$$

Since there are three hydrogen ions ($m = 3$) and one electron ($n = 1$) and $[Fe(OH)_3]$ = 1, then

$$Eh_{(\text{Volts})}=0.994-0.0592\ \log\left[Fe^{2+}\right]-0.178pH \qquad \textbf{(6.47)}$$

Reaction 6.42 $\left(Fe(OH)_4{}^-+H^+\rightleftharpoons Fe(OH)_3+H_2O\right)$ is solved by using an equilibrium approach:

$$\Delta G^0{}_R=\Delta G^0{}_{Fe(OH)_3}+\Delta G^0{}_{H_20}-\Delta G^0{}_{Fe(OH)_4^-}-\Delta G^0{}_{H^+}$$

$$\Delta G^0{}_R=-166-56.69-(-198.4)-0$$

$$\Delta G^0{}_R=-24.29$$

$$\log K_{eq}=-\frac{\Delta G^0{}_R}{1.364}=\frac{24.29}{1.364}=17.8$$

$$K_{eq}=10^{17.8}$$

$$K_{eq}=\frac{\left[Fe(OH)_3\right]\left[H_2O\right]}{\left[Fe(OH)_4{}^-\right]\left[H^+\right]}=10^{17.8}$$

Since $[Fe(OH)_3] = 1$ and $[H_2O] = 1$,

$$\left[H^+\right]=\frac{10^{-17.8}}{\left[Fe(OH)_4{}^-\right]} \qquad \textbf{(6.48)}$$

Equation 6.43 $\left(\mathrm{Fe(OH)_3} + \mathrm{e}^- \rightleftharpoons \mathrm{FeO} + \mathrm{H_2O} + \mathrm{OH}^-\right)$ is solved using the Nernst equation:

$$\Delta G^0{}_R = \Delta G^0{}_{\mathrm{FeO}} + \Delta G^0{}_{\mathrm{H_2O}} + \Delta G^0{}_{OH^-} - \Delta G^0{}_{\mathrm{Fe(OH)_3}}$$

$$\Delta G^0{}_R = -60.03 + (-56.69) + (-37.59) - (-166)$$

$$\Delta G^0{}_R = +\,11.69$$

$$\mathrm{E}^0 = \frac{-\,\Delta G^0{}_R}{nF} = \frac{-\,11.69}{1 \cdot 23.06} = -0.507\,\mathrm{V}$$

$$\mathrm{Eh} \;=\; E^0 - \frac{0.0592}{n}\log\frac{[\mathrm{FeO}][\mathrm{H_2O}][\mathrm{OH}^-]}{[\mathrm{Fe(OH)_3}]}$$

Since $[\mathrm{Fe(OH)_3}] = 1$, $[\mathrm{FeO}] = 1$, $[\mathrm{H_2O}] = 1$, and $n = 1$,

$$\mathrm{Eh} = -\,0.507 - 0.0592\log[\mathrm{OH}^-]$$

Because the diagram uses pH as a variable, $[\mathrm{OH}^-]$ must be expressed in terms of pH. By definition, $[\mathrm{OH}^-] = 10^{-14}/[\mathrm{H}^+]$; therefore, $\log[\mathrm{OH}^-] = \log 10^{-14} - \log[\mathrm{H}^+]$, so that

$$\mathrm{Eh} = -0.5.7 - 0.0592(\mathrm{pH} - 14)$$

$$\mathrm{Eh}_{(\mathrm{volts})} = 0.322 - 0.0592\ \mathrm{pH} \tag{6.49}$$

Reaction 6.44 $\left(\mathrm{Fe(OH)_4}^- + 2\mathrm{H}^+ + e^- \rightleftharpoons \mathrm{FeO} + 3\mathrm{H_2O}\right)$ is solved using the Nernst equation:

$$\Delta G^0{}_R = \Delta G^0{}_{\mathrm{FeO}} + 3\Delta G^0{}_{\mathrm{H_2O}} - \Delta G^0{}_{\mathrm{Fe(OH)_4^-}} - 2\Delta G^0{}_{H+}$$

$$\Delta G^0{}_R = -60.03 + 3(-56.69) - (-198.4) - 0$$

$$\Delta G^0{}_R = -31.7\ \mathrm{kcal/mol}$$

$$E^0 = \frac{-\Delta G^0{}_R}{nF} = \frac{-(-31.7)}{1 \cdot 23.06} = +1.375$$

$$\mathrm{Eh} = E^0 - \frac{0.0592}{n}\log\frac{[\mathrm{FeO}][\mathrm{H_2O}]^3}{[\mathrm{Fe(OH)_4}^-][\mathrm{H}^+]^2}$$

Since $[\mathrm{FeO}]$ and $[\mathrm{H_2O}]$ are 1and $n = 1$,

$$\mathrm{Eh} = +\,1.375 - 0.0592\log\frac{1}{[\mathrm{Fe(OH)_4}^-][\mathrm{H}^+]^2}$$

This can be expressed in terms of pH as

$$\text{Eh} = 1.375 + 0.0592 \log\left[\text{Fe(OH)}_4^{\ -} + 2(0.0592) \log\left[\text{H}^+\right]\right.$$

$$\text{Eh}_{(\text{volts})} = 1.375 + 0.0592 \log\left[\text{Fe(OH)}_4^{\ -}\right] - 0.118\text{pH} \quad \textbf{(6.50)}$$

Reaction 6.45 ($\text{FeO} + 2\text{H}^+ \rightleftharpoons \text{Fe}^{2+} + \text{H}_2\text{O}$) is solved as an equilibrium reaction:

$$\Delta G^0{}_R = \Delta G^0{}_{\text{Fe}^{2+}} + \Delta G^0{}_{\text{H}_2\text{O}} - \Delta G^0{}_{\text{FeO}} - 2\Delta G^0{}_{H^+}$$

$$\Delta G^0{}_R = -18.85 + (-56.69) - (-60.03) - 2(0)$$

$$\Delta G^0{}_R = -15.51 \text{ kcal/mol}$$

$$\log k_{eq} = \frac{-\Delta G^0{}_R}{1.364} = 11.36$$

$$k_{eq} = 10^{11.36}$$

$$k_{eq} = \frac{[\text{Fe}^{2+}][\text{H}_2\text{O}]}{[\text{FeO}][\text{H}^+]^2}$$

Since $[\text{H}_2\text{O}]$ and $[\text{FeO}] = 1$,

$$[\text{H}^+]^2 = \frac{[\text{Fe}^{2+}]}{10^{11.36}}$$

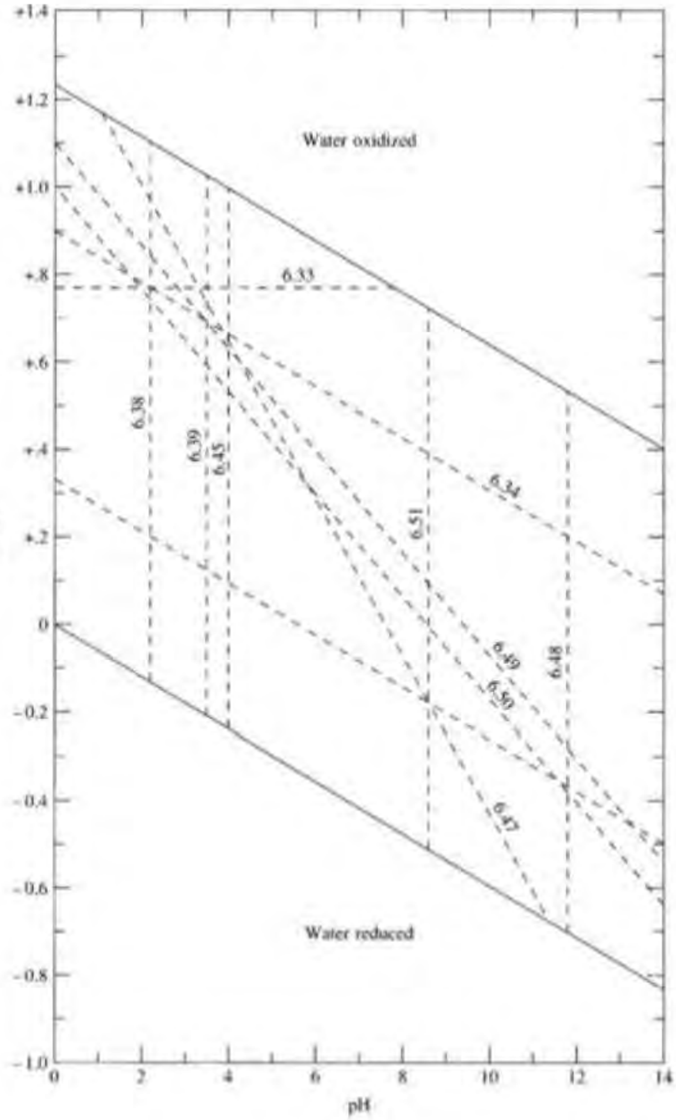
$$[\text{H}^+] = \sqrt{\frac{[\text{Fe}^{2+}]}{10^{11.36}}} \quad \textbf{(6.51)}$$

Several of the equations, including Equations 6.46, 6.47, 6.48, 6.50, and 6.51, depend upon the activity of the dissolved iron.

The following equations, which are independent of dissolved iron activity, have been derived.

Boundary	**Equation Number**	**Equation**
$\text{FeOH}^{2+} - \text{Fe}^{2+}$	6.31	$\text{Eh}_{(\text{volts})} = 0.898 - 0.0592\text{pH}$
$\text{Fe(OH)}_2^+ - \text{Fe}^{2+}$	6.32	$\text{Eh}_{(\text{volts})} = 1.107 - 0.118\text{pH}$
$\text{Fe}^{3+} - \text{Fe}^{2+}$	6.33	$\text{Eh}_{(\text{volts})} = 0.770$
$\text{Fe}^{3+} - \text{FeOH}^{2+}$	6.38	$\text{pH} = 2.17$
$\text{Fe(OH)}^{2+} - \text{Fe(OH)}_2^+$	6.39	$\text{pH} = 3.53$
$\text{Fe(OH)}_3 - \text{FeO}$	6.49	$\text{Eh}_{(\text{volts})} = 0.322 - 0.0592\text{pH}$

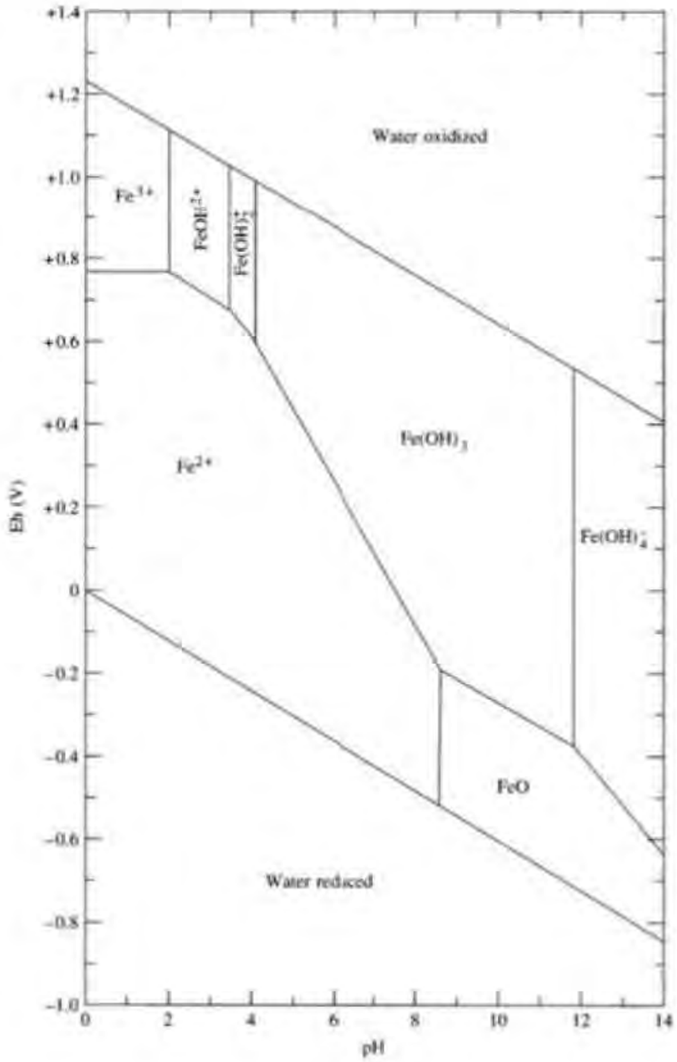
FIGURE 6.3 Equations for an Eh-pH diagram for dissolved iron with dissolved iron activity of 10^{-6} Mol under standard conditions. (Numbers adjacent to dotted lines refer to equations discussed in the text.)



The iron Eh-pH diagram of Figure 6.4 is for a system that contains only dissolved iron. If other elements are present, such as sulfur, then additional iron compounds are possible. Figure 6.5 shows an Eh-pH diagram for a system with an iron activity of 56 μg/L (10^{-6} mol), sulfur of 96 mg/L as SO_4^{2-}, and carbon dioxide of 61 mg/L as HCO_3^-. Solids in the shaded area are thermodynamically stable. Under the conditions specified in this diagram, iron carbonate ($FeCO_3$) saturation was not reached and none is recorded as a solid phase.

The area of the region in which iron is precipitated rather than dissolved is a function of the concentration of dissolved iron. The more dissolved iron that is present, the greater the size of the stability field for the precipitates. This is illustrated in Figure 6.6. In this diagram the sulfur is 96 mg/L as SO_4^{2-}– and the carbonate is 61 mg/L as HCO_3^-. Dissolved iron ranges from 5.6 μg/L to 56 mg/L.

FIGURE 6.4 Final Eh-pH diagram for a dissolved iron system with dissolved iron at 10^{-6} moles under standard conditions.



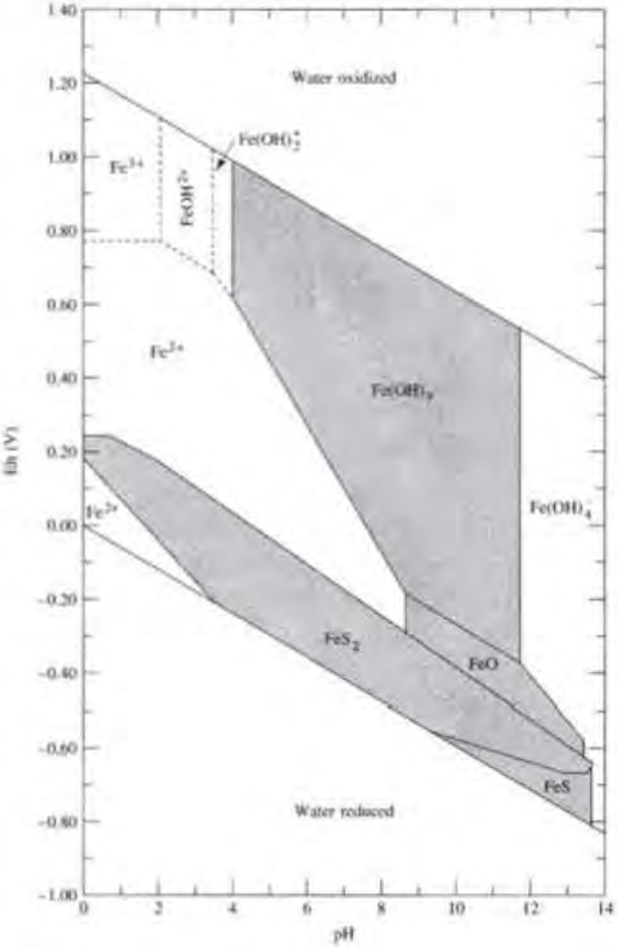
Eh-pH diagrams have been used in the ground-water literature to explain such phenomena as the solubility of ferric oxyhydroxides (Whittemore and Langmuir 1975), hexavalent chromium (Robertson 1975), manganese (Hem 1985), iron, copper, silver, chromium, manganese, vanadium, molybdenum, and arsenic (Hem 1977), uranium (Langmuir 1978), thorium (Langmuir and Herman 1980), and arsenic (Matisoff et al. 1982).

6.6 Metal Complexes and Facilitated Particle Transport

6.6.1 Hydration of Cations

Although we consider that metallic ions exist in solution as an isolated ion, such as Cu^{2+}, in fact that is not the case. The Cu^{2+} ion is surrounded by polar water atoms that are chemically bound to the ion. Metallic ions, in general, have six water molecules

FIGURE 6.5 Eh-pH diagram showing fields of stability for dissolved iron under standard conditions. Activity of dissolved iron is 10^{-6} mol (56 µg/L), of sulfur species is 96 mg/L as SO_4^{2-}, and of carbon dioxide species is 61 mg/L as HCO_3^-.



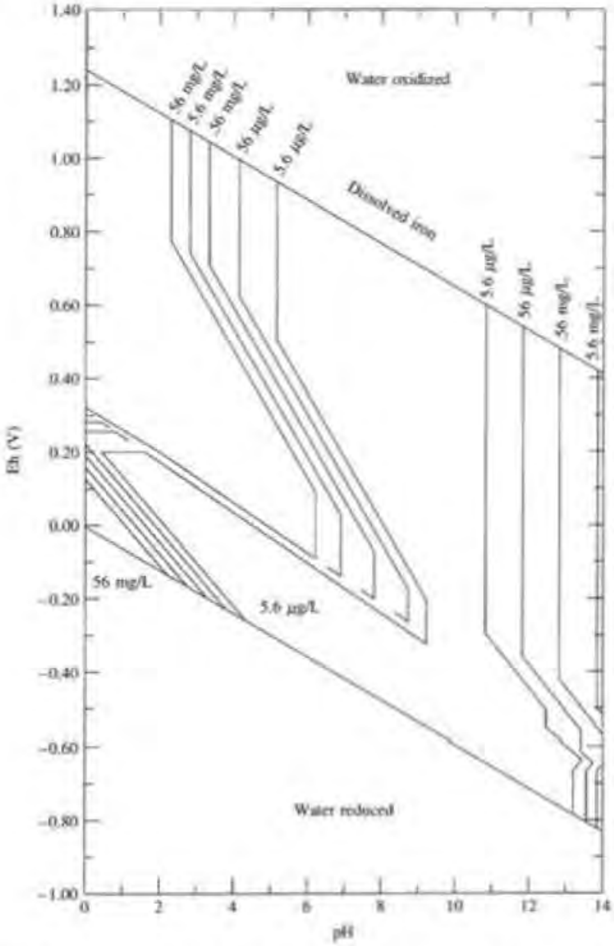
Source: J. D. Hem. 1985. *Study and interpretation of the chemical characteristics of natural waters*. Water Supply Paper 2254, U.S. Geological Survey.

surrounding them. The hydrated cupric ion is $Cu(H_2O)_6^{2+}$. Even outside the shell of chemically bound water molecules, there is a region where the polar water molecules are ordered by the electrostatic charge of the metallic ion. Anions in close association with a metal cation are called **ligands**; together they form a coordination compound. Water is considered to be a **ligand** that is bound to the metal ion. If other ligands bind to the metal, they must replace some of the water molecules acting as ligands. The stability of a complex relative to cation or ligand exchange can be described by equilibrium constants for the reaction.

6.6.2 Complexation

The following inorganic anions act as simple ligands in natural waters: OH^-, CO_3^{2-}, SO_4^{2-}, Cl^-, Br^-, F^-, NO_3^-, SiO_3^{2-}, S^{2-}, $S_2O_3^-$, PO_4^{3-}, $P_2O_7^{4-}$, $P_3O_{10}^{5-}$, and CN^-. Ammonia (NH_3) is a polar molecule that can also act as a ligand. Ligands can bond either covalently or electrostatically with a metal to form a complex ion or compound. We have already

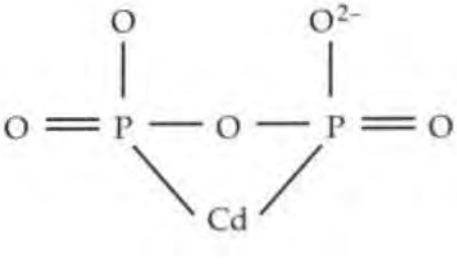
FIGURE 6.6 Equilibrium activity of dissolved iron as a function of Eh and pH under standard conditions, sulfur activity of 96 mg/L as SO_4^{2-} and activity of carbon dioxide of 61 mg/L as HCO_3^-.



Source: J. D. Hem. 1985. *Study and interpretation of the chemical characteristics of natural waters.* Water Supply Paper 2254, U.S. Geological Survey.

looked at the complex forms of the ferric ion and the hydroxyl ion. They form a series of complex ions: $FeOH^{2+}$, $Fe(OH)_2^+$, $Fe(OH)_3$ and $Fe(OH)_4^-$. Complex formation is involved with chemical equilibrium of ionic compounds and oxidation-reduction reactions.

In the case of monovalent ions, there is only one site where the ligand bonds to the metal ion and the ligand is called monodentate (literally, "one tooth"). If the ligand has more than one site that can bond (polydentate), then it forms what is known as a **chelating agent**. For example, the pyrophosphate ion, $P_2O_7^{4-}$, can bond to a metal ion, such as cadmium, at two locations:



6.6.3 Organic Complexing Agents

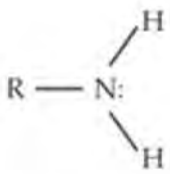
Both natural waters and wastewaters contain a number of organic compounds that can act as chelating agents. In general, these organic compounds have a functional group that contains oxygen, nitrogen, phosphorous, or sulfur. If R symbolizes one or more carbon atoms with the appropriate number of hydrogens, then organic complexes can include functional groups such as

$R-C(=O)-O^-$

Carboxylate

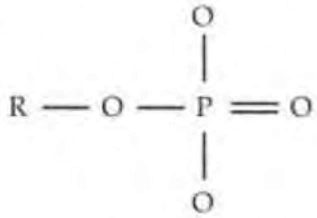
$R-OH$

Alcohol



$R-\ddot{N}H_2$

Amine



$R-O-P(=O)(O)-O$

Phosphate

There are a number of organic complexing agents that occur in nature. They are associated with **humic substances** that form from the decomposition of vegetation. These are complex organic molecules with molecular weights ranging upward into the tens of thousands. If a humic substance is extracted with a strong base and then acidified, there are three products. The nonextractable organic material is called **humin**. Substances called **fulvic acids** remain in the acidic solution, and other substances called **humic acids** precipitate from the acidified extract. These represent classes of compounds that contain many different individual organic molecules. Humic and fulvic acids contain many functional groups that can chelate to metals. Metals may be kept in solution by chelation with soluble fulvic acids or they may bind to the insoluble humic substances by cation exchange (Manahan 1984).

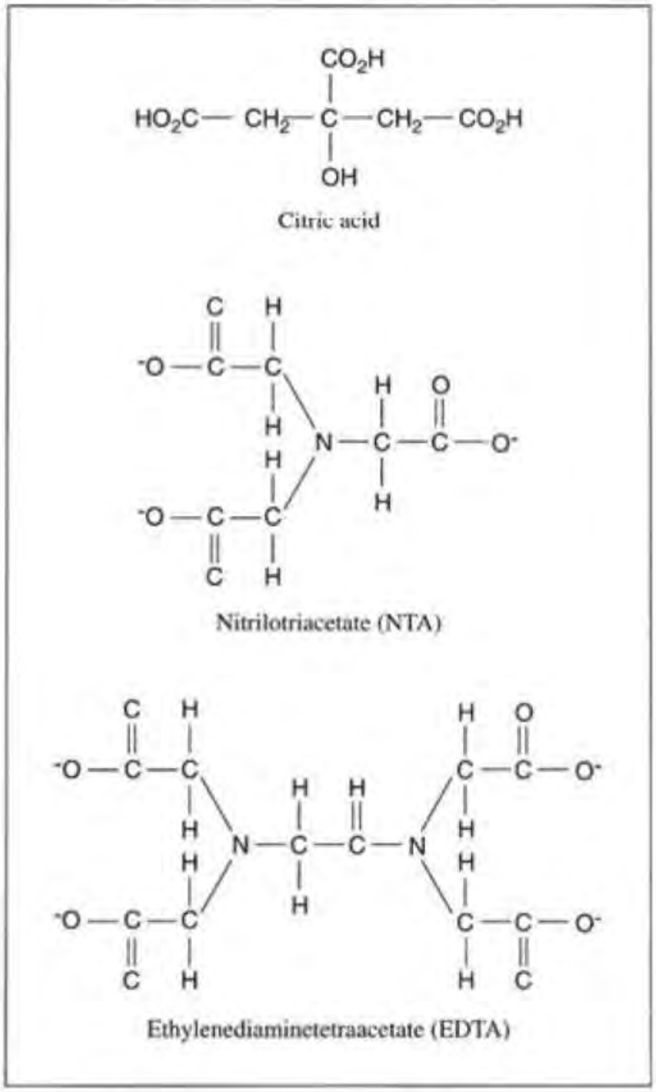
Synthetic organic complexing agents are used in a number of industrial processes. They can be used as cleaning compounds, as constituents of detergent, in metal plating baths, and in water conditioning. These compounds include sodium tripolyphosphate, sodium ethylenediaminetetraacetate (EDTA), citric acid, and sodium nitrilotriacetate (NTA). The structures of some of these compounds are given in Figure 6.7. Synthetic chelating agents may keep metals in solution under conditions where the unchelated metal would precipitate or undergo cation exchange.

EDTA in wastewater can vastly increase the mobility of associated metals in the subsurface. Monitoring wells near radioactive waste disposal trenches at the Oak Ridge (Tennessee) National Laboratory contained significant levels of sodium EDTA, which was used as a cleaning agent. The same wells also contained radioactive ^{60}Co, a metal that is normally not expected to migrate very far due to cation exchange. The ^{60}Co had been chelated by the EDTA and hence had greatly increased mobility in the subsurface (Means et al. 1978).

6.6.4 Facilitated Particle Transport

Many metals and other inorganic compounds have a great sorptive capacity and an affinity for particles suspended in water. Normally in subsurface environments this limits contaminant mobility in that most mobile particles and colloids are filtered out of flowing groundwater in porous media. However, particles suspended in groundwater

FIGURE 6.7 Structure of chelating agents including (a) citric acid, (b) nitrilotriacetate (NTA), and (c) ethylenediaminetetraacetate (EDTA).



can be mobilized in flow through fractured rock or karst rocks where groundwater moves through larger conduits and suspended particles are not filtered by the geologic medium. Contaminants sorbing on these particles, including many metals, essentially can "hitch a ride" on moving grains and colloids and this can increase the effective speed of contaminant movement through aquifers by orders of magnitude. This enhanced mobility is called **facilitated particle transport**.

Facilitated particle transport can pose problems in modeling contaminant movement and dispersion because of accelerated movement, and also impact the representativeness of groundwater sampling protocols. Many standard techniques for measuring metal concentrations in groundwater require samples to be filtered and acidified in the field. In conditions where groundwater contains contaminants sorbed on suspended particles and colloids, some practitioners collect both filtered and unfiltered samples for comparative chemical analysis.

6.7 Chemistry of Nonmetallic Inorganic Contaminants

6.7.1 Fluoride

Fluoride occurs in water as the F^- ion. In natural waters the amount of fluoride present is generally less than 1.0 mg/L, although concentrations as great as 67 mg/L have been reported (Hem 1985). Fluoride is present in minerals such as fluorite (CaF_2) and apatite ($Ca_5(Cl,F,OH)(PO_4)_3$). Weathering of these minerals may release fluoride. It may be released as a contaminant from industrial processes utilizing hydrofluoric acid. Cryolite (Na_3AlF_6) is used as a flux in the electrolytic production of aluminum. The manufacture of phosphate fertilizer from phosphate-rich rock may also release fluoride. Effluent from a Florida fertilizer plant had fluoride ranging from 2810 to 5150 mg/L (Cross and Ross 1970).

Fluoride can form complexes in water with a number of cations, including aluminum, beryllium, and ferric iron (Hem 1985). Dissolved fluoride can react with calcium to form fluorite. The solubility product for fluorite is $10^{-10.4}$. Precipitation of fluorite can act as a control on the amount of dissolved fluoride in solution if dissolved calcium is present. Table 6.5 shows the equilibrium amount of dissolved fluoride calculated for various activities of calcium. Actual activities of fluoride are likely to be somewhat higher due to the effect of the ionic strength of the solution as well as the effect of any complexes that might form with the fluoride ion.

Fluoride can dissolve into groundwater from anthropogenic sources, but also from volcanic activity and other natural geologic sources through subsurface rock-water interaction. Magmatic fluorine is often in the form of hydrogen fluoride (HF) which is one of the most soluble gases in magmas, exsolving from molten rock only partially, and leaving large amounts of fluoride in cooled volcanic and plutonic rocks. High subsurface temperatures and acidic conditions enhance the dissolution of fluoride from these rocks into groundwater. Portions of the earth's large magmatic provinces, such as the Deccan flood basalts of India, the Siberian traps of central Asia, and the East African Rift Valley are endemic for fluorosis from consumption of high fluoride concentration in groundwater, as are smaller more isolated locales at the base of volcanoes (Brindha and Elango 2011; D'Alessandro 2006).

Corbett and Manner (1984) have reported on the distribution of fluoride in water from both unconsolidated and bedrock aquifers of northeastern Ohio. They found that 239 out of 255 wells had fluoride concentrations less than 1mg/L. However, 14 of

TABLE 6.5 Equilibrium fluoride concentrations as a function of calcium activity.

Calcium		Fluoride	
Activity (mol)	Concentration (mg/L)	Activity (mol)	Concentration (mg/L)
2×10^{-2}	800	4.48×10^{-5}	0.85
10^{-2}	400	6.31×10^{-5}	1.20
5×10^{-3}	200	8.92×10^{-5}	1.70
10^{-3}	40	2.00×10^{-4}	3.79
5×10^{-4}	20	2.82×10^{-4}	5.36
10^{-4}	4	6.31×10^{-4}	11.99

the wells had fluoride ranging from 1 to 5.9 mg/L. All these high-fluoride wells were associated with a specific bedrock formation. Such information is useful from a public health standpoint because there is a 2.0-mg/L drinking-water criteria for fluoride. Some fluoride is needed to build strong teeth in growing children; however, fluoride in excess of 2.0 mg/L will cause teeth to discolor. Chronic ingestion of high fluoride in drinking water can also produce a serious condition known as skeletal fluorosis, which can damage bones and joints.

6.7.2 Chlorine and Bromine

The halides chlorine and bromine have similar chemistry, although chlorine is far more abundant in nature than bromine. Even though the elements can exist in a number of oxidation states, the chloride and bromide ions (Cl^-, Br^-) are the only ones of significance in natural waters. These halides are widely distributed in rocks and soil, and can be naturally leached into groundwaters. The chloride ion occurs in natural waters in fairly low concentrations, usually less than 100 mg/L, unless the water is brackish or saline. Chloride is used by humans in many applications and can be added to the subsurface via industrial discharges, sewage, animal wastes, and road salting. Chlorine gas is used as a disinfectant for purification of water and is a strong oxidizing agent when dissolved in water. Commercial fertilizers can contain chloride as KCl. Chlorine and bromine are components of halogenated organic compounds used for industrial solvents and pesticides. These compounds have been released to the environment both intentionally through the use of pesticides and accidentally through spills and leaks. Recent increases in shale hydrocarbon development have produced large quantities of post-fracking brine waters (which flow back upwards to the surface after well development), as has brine production from dewatering associated with coal bed methane extraction (also called coal seam gas). These large quantities of brine have increasingly been disposed of through underground injection. Fracking flowback water with Cl^- concentrations as high as 151,000 mg/L have been reported (Haluszczak et al. 2013).

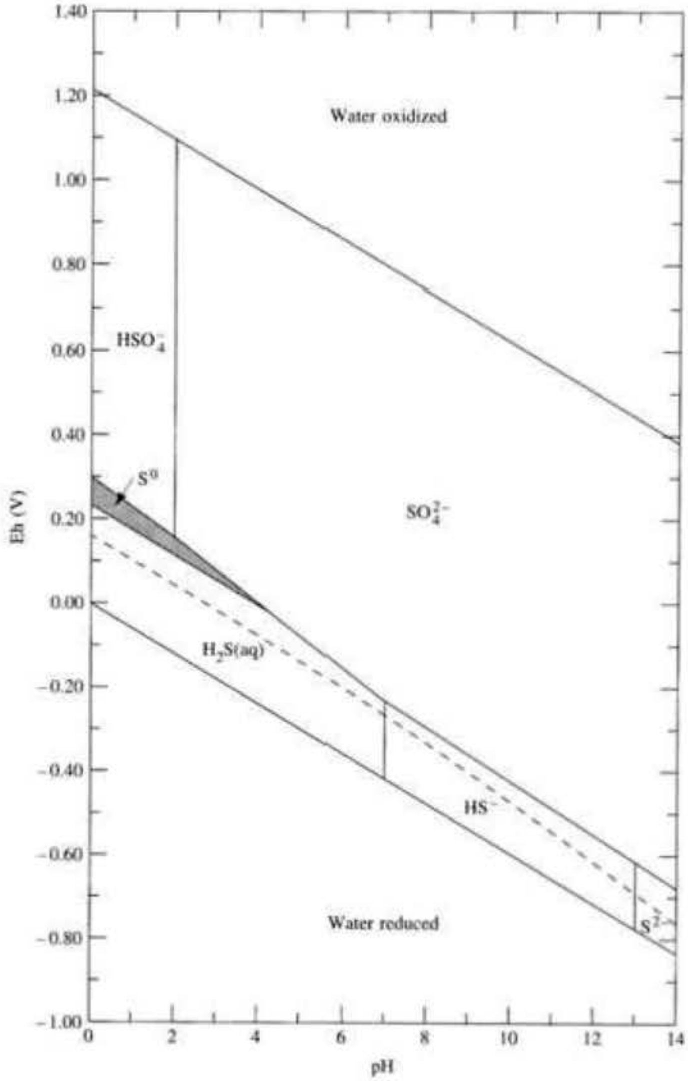
Chloride and bromide ions are not reactive. They don't participate in redox reactions, aren't sorbed onto mineral or organic surfaces, and don't form insoluble precipitates. Chloride is sometimes used as a tracer in groundwater studies because it is conservative. Distinctive ratios of Cl^- and Br^- and other elements in groundwater have been valuable in reconstruction groundwater's movement and origin, including determining mixing ratios of different source waters. These ions are highly mobile in the subsurface and are often eventually transported to closed basins or oceans. Additionally, concentrations of chlorine isotopes in groundwater have effectively been used for groundwater dating techniques, including bomb-pulse chlorine-36 put into atmosphere with nuclear weapons testing and falling with rainfall, infiltrating and percolating into groundwater (Challan 2016). These forensic groundwater analytical techniques aid in the tracking of groundwater pollution (see Chapter 8).

6.7.3 Sulfur

Sulfur is naturally released to the environment by the weathering of minerals containing the element. Rock containing pyrite can be oxidized to release sulfur, with microorganisms acting as a catalyst and mediating the oxidation. This is the source of the acidic water that drains from many areas that have been mined. Sulfuric acid is widely used in industrial processes. Sulfur can be released to the environment by the processing of sulfide ores and by the burning of fossil fuels, all of which contain sulfur to some degree. Sulfur is also a component of many fertilizers and can leach into groundwater systems from agricultural sources.

Sulfur can exist in valence states ranging from S^{-2} to S^{+6}. Figure 6.8 is an Eh-pH diagram showing the stability of the two oxidized forms of sulfur, $HSO4^{-}$ and SO_4^{2-}, and the three reduced forms, S^{2-}, HS^{-}, and H_2S (aqueous). The field of stability for elemental sulfur is also shown. The total sulfur activity used in computing the diagram is 10^{-3} mol/L or 96 mg/L as. SO_4^{2-}. If a greater total sulfur activity were used, the stability field for elemental sulfur would be larger. Although this is a very useful diagram

FIGURE 6.8 Eh-pH diagram for sulfur species at standard conditions with total dissolved sulfur activity of 96 mg/L.



Source: J. D. Hem. 1985. *Study and interpretation of the chemical characteristics of natural waters*. Water Supply Paper 2254, U.S. Geological Survey.

for understanding the equilibrium conditions for dissolved sulfur, the redox reactions can be slow if microbes are not mediating the reactions. Hence, it may take a long time for the system to reach equilibrium.

Gypsum (calcium sulfate) is quite soluble in water ($K_{eq} = 10^{-4.6}$) and, except for waters with extremely high sulfate, would not be a sink for sulfate. Strontium sulfate is sparingly soluble ($K_{eq} = 10^{-6.5}$), whereas barium sulfate is nearly insoluble ($K_{eq} = 10^{-10.0}$). However, strontium and barium are not found in much abundance in natural waters. Sulfate could act as a sink for strontium and barium. Sulfur isotopes can be used to distinguish pollutant sources in some cases.

6.7.4 Nitrogen

Nitrogen is another element that can occur in both oxidized and reduced forms as well as the elemental state. The common forms of inorganic nitrogen include nitrate, NO_3^-, nitrite, NO_2^-, nitrogen gas, N_2, ammonium, NH_4^+, and cyanide, CN^-. Nitrogen is also a major constituent of organic matter in the form of amino acids. The majority (78%) of the Earth's atmosphere is nitrogen gas. Atmospheric nitrogen can be "fixed", or converted to nitrate, by cyanobacteria in lakes and the ocean and by bacteria living on the roots of plants such as legumes and lichens. Atmospheric nitrogen can also be converted to oxidized and reduced forms via fertilizer production and by heating it to high temperatures in internal combustion engines, power plants, lightning discharges and forest fires. Rainwater contains dissolved nitrate and ammonia. Nitrogen is released to the subsurface from sewage, animal wastes, and fertilizers.

In soil and groundwater, oxidation and reduction of nitrogen species is accomplished by microorganisms. Under oxidizing conditions ammonia is converted to nitrite, which is converted to nitrate. Nitrite is a very reactive ion and is almost immediately converted to nitrate, so that little nitrite is normally found in the environment. Under reducing conditions nitrate is converted primarily to nitrogen gas, a process known as **denitrification**. Organic matter will decay to ammonia under reducing conditions. Septic tank effluent, for example, normally has high ammonia and very little nitrate. If the receiving groundwater is reducing, the nitrogen will stay in the ammonia form. If it is oxidizing, bacteria will convert the ammonia to nitrate (Feth 1966). Nitrate is chemically conservative, can be mobile in the subsurface environment, and understandably, high nitrate concentrations in drinking water are most often associated with privately owned wells. Since the 1940s, health concerns and regulatory standards for nitrogen in groundwater center on infant methemoglobinemia (commonly called the "blue baby" disease). The high gastric pH of infants and their great fluid intake relative to body weight contribute to their internal bacterial reduction of ingested nitrate to nitrite, and the generated nitrite inhibits the function of blood hemoglobin in the transfer of oxygen.

Nitrate contamination of groundwater has been documented in a number of areas (e.g., Hill 1982; Flipse et al. 1984; and Silver and Fielden 1980). Hill studied the distribution of nitrate in groundwater from a shallow unconsolidated sand aquifer. It was found that the groundwater beneath areas of forest or permanent pasture has less than 1.0 mg/L of nitrate as nitrogen. The groundwater beneath heavily fertilized potato fields typically contained in excess of 10 mg/L nitrate as nitrogen. Gray and Morgan-Jones (1980) found that the nitrate content of groundwater in a study area increased over the past 40 years and that the use of fertilizers in this catchment area also increased over the same time period.

Nitrogen occurs as two isotopes, ^{14}N and ^{15}N. Of the two, ^{14}N is by far the most abundant in the atmosphere. The relative abundance of ^{15}N—that is, the ^{15}N/^{14}N ratio—in nitrate may be used to distinguish nitrate that comes from animal and human waste from nitrate that comes from mineral fertilizers (Flipse et al. 1984).

The ^{15}N/^{14}N ratio is usually expressed as a δ^{15}N value, which is defined as

$$\delta^{15}\mathrm{N}(\%_{0}) = \frac{\left({}^{15}\mathrm{N}/{}^{14}\mathrm{N}\right)\mathrm{sample} - \left({}^{15}\mathrm{N}/{}^{14}\mathrm{N}\right)\mathrm{standard}}{\left({}^{15}\mathrm{N}/{}^{14}\mathrm{N}\right)\mathrm{standard}} \times 1000$$

where ‰ stands for parts per thousand.

If the δ^{15}N is positive, then the nitrate of the sample has been enriched in ^{15}N with respect to the standard. For nitrogen, the standard is the atmospheric composition. Nitrate from animal and human waste typically has a δ^{15}N in excess of +10‰.

Flipse and Bonner (1985) found that mineral fertilizers used on Long Island had δ^{15}N values that averaged 0.2‰ at one site and –5.9‰ at another. However, the δ^{15}N of the groundwater beneath the sites that had been fertilized was about +6‰. This increase in δ^{15}N from the mineral fertilizer was attributed to fractionation that occurred during infiltration of the nitrogen. However, the resulting δ^{15}N was still clearly lower than that expected from animal and human waste.

6.7.5 Arsenic

Arsenic can occur in valence states of +5, +3, +1, 0 and –3. However, the important states of dissolved arsenic in water are the arsenate $H_nAsO_4^{3-n}$, with a valence state of +5, and the arsenite $H_nAsO_3^{2-n}$, with a valence state of +3. An Eh-pH diagram for arsenic that shows the fields of stability for the arsenates and arsenites is given in Figure 6.9. Dissolved arsenic species can be absorbed by ferric hydroxides. Arsenic (+5) is more strongly sorbed than arsenic (+3). Ferric hydroxides are stable over a wide Eh-pH range, so this fact limits the mobility of arsenic. However, conditions that reduce Fe^{3+} to Fe^{2+} and As^{5+} to As^{3+} increase the mobility of arsenic in the environment, because the precipitated ferric hydroxides become soluble ferrous hydroxides (Matisoff et al. 1982). In an oxidizing environment with a pH above 4.09, we will find colloidal ferric iron hydroxides, which will sorb arsenic and would thus expect to have little arsenic in solution. Under strongly reducing conditions, if both iron and hydrogen sulfide are present, arsenic sulfide coprecipitates with iron sulfide. Mildly reducing conditions that lack hydrogen sulfide present conditions under which one would expect to find the most mobile arsenic, as iron would be in the soluble ferrous state and arsenic would be in the arsenite form (Hounslow 1980).

Arsenic has been released to the environment through the burning of coal and the smelting of ores. In the past it was used in the formulation of insecticides and embalming corpses. Starting at the time of the Civil War in the United States (1860–1865), arsenic was an ingredient in a popular embalming fluid. As much as 3 lb of arsenic could have been used per corpse. The use of arsenic in embalming fluids was banned by the federal government in 1910 because its use interfered with the investigation of suspected arsenic poisonings. However, graveyards from the Civil War and the late nineteenth century may be a source of arsenic contamination (Konefes 1990). It has some modern industrial uses. Groundwater has been found to have high (up to 96 μg/L) concentrations from natural sources in northeastern Ohio (Matisoff et al. 1982). Elevated arsenic (up to 5 mg/L) in groundwater in Nova Scotia, Canada, was reportedly due to the weathering of piles of mining waste that contained arsenopyrite (Grantham and Jones 1977). In the western United States high (>50 μg/L) concentrations of arsenic are common in groundwater. These are associated with areas of sedimentary rocks derived from volcanic areas, geothermal systems and gold and uranium mining districts. Irrigation in some areas has liberated arsenic to the extent that concentrations of up to 1 mg/L are found in shallow groundwater beneath irrigated fields (Welch, Lico, and Hughes 1988).

Naturally occurring arsenic in groundwater can also be a huge problem. In what one writer called "one of the largest mass poisonings in history," thousands of tube wells were drilled in shallow aquifers contaminated with naturally-occurring arsenic in Bangladesh and India in the 1980s and 1990s before the problem was recognized (Brahic 2004). As a result, arsenic has posed risk to an estimated 57 million people in Bangladesh (Hossain 2006), and 100,000 are estimated to have been affected by high concentrations in shallow well water in the region (Brahic 2004). Annually, another 270,000 have been estimated to have had cancer related deaths, as long-term exposure to arsenic has been related to cancer of the kidneys, lungs, bladder and skin (Brahic 2004). The problem was unrecognized for many years, in part because a study by the British Geological Survey (BGS) and Britain's National Environment Research Council (NERC) did not adequately test for arsenic in reconnaissance groundwater quality surveys which subsequently served as the basis for drawing up national water policies and the drilling of thousands of wells.

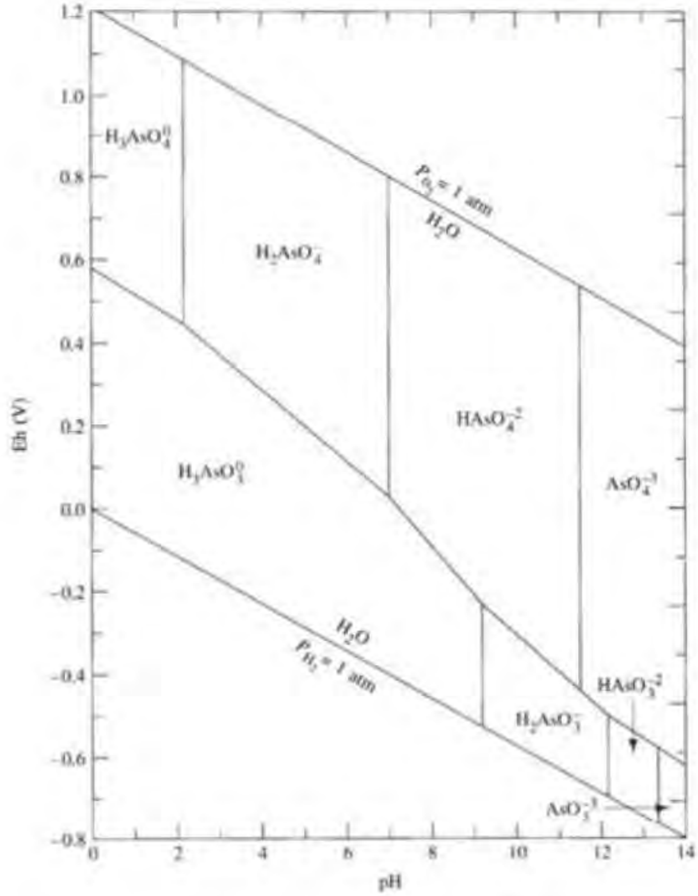
6.7.6 Selenium

Selenium occurs in oxidizing solutions as selenite, SeO_3^{2-}, with a +4 valence and as selenate, SeO_4^{2-}, with a +6 valence. It can be reduced to the insoluble elemental form, Se^0. It may also form a precipitate ferroselenite, $FeSe_2$, under reducing conditions. Selenite may be sorbed onto amorphous ferric hydroxides. Selenium has a number of industrial uses, such as the manufacture of pigments, stainless steel, and rubber compounds. It is contained in phosphate fertilizers. Selenium has been known to concentrate in irrigation return water draining from land that has soil high in selenium, and can be present in waste liquids from metal smelting. It is naturally present in coal, particularly bituminous coal, and can be concentrated approximately 1,250 times in the burning process at coal-fired power plants (coal versus precipitator ash), and can be present in elevated concentrations in waste scrubber water, ash ponds or other liquid wastes which could leach and percolate into the subsurface.

In small concentrations selenium is an essential nutrient, but in large amounts it is harmful to humans, fish, and wildlife (Coefield 2009). High selenium in groundwater-dependent ecosystems can wipe out entire species and cause massive wildlife and fish kills. High selenium has been problematic at many sites and from activities worldwide, including (Lemly 2002):

1. Nickel and silver mining in Torun, Poland.
2. Municipal landfill leachates in Stockholm, Sweden; Minnesota, U.S.A.; and in London, U.K.
3. Irrigation runoff in Chihuahua, Mexico; Utah, U.S.A.; and in Kesterson National Wildlife Refuge, California, U.S.A.
4. Coal combustion waste in Texas, Pennsylvania, Kentucky, North Carolina, U.S.A. and Alberta Canada.
5. Phosphate mining waste in Idaho, U.S.A.
6. Gold mining waste in Buenos Aires, Argentina; Quito, Ecuador; and Yukon, Canada.
7. Metal smelting waste in Ontario, Canada.
8. Oil-refinery waste in Louisiana, U.S.A.

FIGURE 6.9 Eh-pH diagram for arsenic species under standard conditions.



Source: A. H. Welch, M. S. Lico, and J. L. Hughes. 1988. Arsenic in ground water of the western United States. *Groundwater* 26:333–347. Used with permission.

6.7.7 Phosphorus

Phosphorus can occur in a number of valence states, but in natural water it is really significant only in the +5 state. Dissolved phosphorus in water occurs as phosphoric acid (H_3PO_4) and its dissociation products, the orthophosphate ions: $H_2PO_4^-$, HPO_4^{2-} and PO_4^{3-}.The proportion of each present in an aqueous solution is a function of pH. Dissolved phosphorus is readily sorbed onto soil and has a very low mobility in groundwater. in alkaline soils it can react with calcium carbonate to form a mineral precipitate, hydroxyapatite.

$$3HPO_4{}^{2-} + 5CaCO_3 + 2H_2O \rightarrow Ca_5(PO_4)_3(OH) + 5HCO_3{}^- + OH^-$$

Phosphate is released to the environment from mineral fertilizers, animal wastes, sewage, and detergents.

6.8 Chemistry of Metals

Metals are cations, and most have fairly limited mobility in soil and groundwater because of cation exchange or sorption on the surface of mineral grains. They can also form precipitates of varying solubility under specific Eh-pH conditions. Geologically, metal ores are typically in the form of sulfides, oxides, silicates, or "native" metals. Metals are mobile in groundwater if the Eh-pH range is such that soluble ions exist and the soil has a low cation-exchange capacity (Dowdy and Volk 1983). They can also be mobile if they are chelated or if they are attached to a mobile colloid. Conditions that promote mobility include an acidic, sandy soil with low organic and clay content. Discharge of a metal in an acidic solution would keep the metal soluble and promote mobility.

6.8.1 Beryllium

Beryllium occurs only in the +2 valence state. In natural waters we can have Be^{2+}, $Be(OH)^+$, $Be(OH)_2$ and $Be(OH)_3^-$. Beryllium oxide and hydroxide have low solubilities and can act as a control on beryllium concentration. At equilibrium with $Be(OH)_2$, the dissolved form would have an activity of about 100 μg/L at a pH of 6 (Hem 1985). Nonetheless, beryllium can find its way into groundwater from industrial wastewater discharges or from natural weathering and dissolution of rocks, particularly igneous rock containing granites and pegmatites. Beryllium is used for making metal alloys for the aerospace industry, nuclear reactors, and is used in electrical equipment and microwave ovens.

6.8.2 Strontium

Strontium also occurs in the +2 valence state and has a chemistry similar to that of calcium. The solubility product for strontium sulfate, $SrSO_4$, is $10^{-6.4}$. This suggests that there might be an equilibrium control on strontium concentration if sulfate is present in the water. Strontium carbonate, $SrCO_3$, has a solubility product of 10^{-10}. In general, strontium is present in groundwaters in concentrations of less than 1mg/L.

However, in tracing groundwater pathways and subsurface movement of potential contaminants, the isotopic ratio of $^{87}Sr/^{86}Sr$ can be a "powerful tool in distinguishing among solute sources," as the ratio can reflect mineral interaction with groundwater, differences in initial water quality, recharge waters of varying evaporative concentrations or pCO_2 concentration, and differences in relative mobilities of different groundwaters (USGS 2015).

6.8.3 Barium

This alkaline earth element also has a valence of +2. Its distribution is controlled by the solubility of barite, $BaSO_4$. Barite has a solubility product of 10^{-10}. If the activity of sulfate is 96 mg/L (10^{-3} *M*), then the activity of barium is 10^{-7} *M*, or 0.014 mg/L. Barium is also found as witherite ($BaCO_3$), and other compounds, but is not found in the environment as a free element because of its high reactivity. Barium sulfate can be an additive to oil-well drilling fluid, medical waste, and because in its ionic form barium is soluble and toxic, it is a component of some rodenticides.

6.8.4 Vanadium

This transition metal has oxidation states of + 3, +4, and +5. In aqueous solutions it forms 10 different oxides and hydroxides. Dissolved iron can react with vanadium to form an insoluble ferrous vanadate, which can act as a control on vanadium in natural water (Hem 1977).

$$\mathrm{FeOH^+ + 2H_2VO_4^- + H^+ \rightleftharpoons Fe(VO_3)_2 + 3H_2O}$$

6.8.5 Chromium

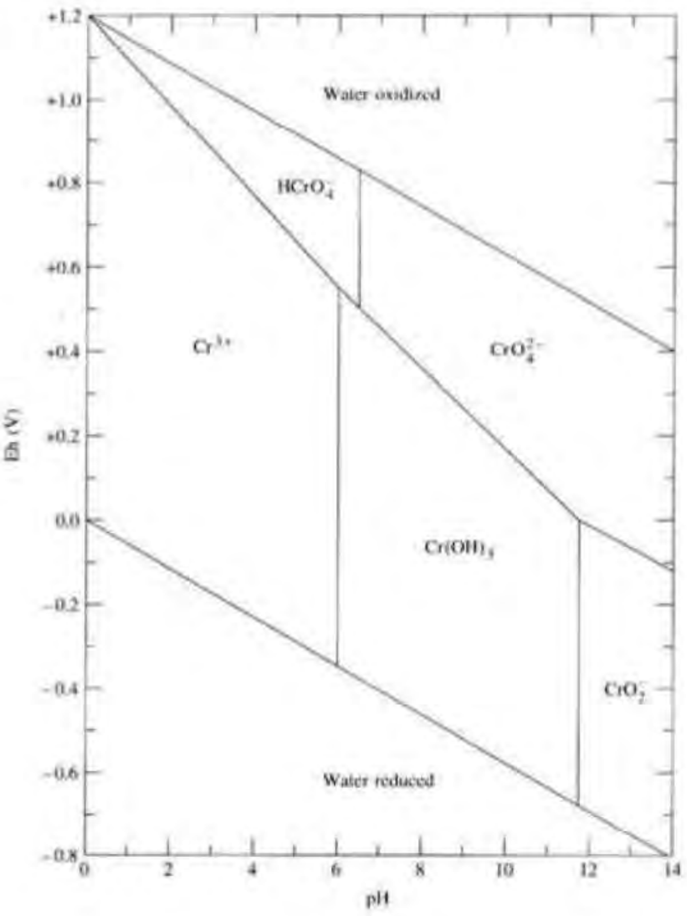
Chromium in natural waters occurs in a +3 and a +6 valence state. Stable ionic forms in aqueous systems include Cr^{3+}, $CrOH^{2+}$, $Cr(OH)_2^+$, $Cr_2O_7^{2+}$ and CrO_4^{2-}. Chromous hydroxide, $Cr(OH)_3$ is a possible precipitate under reducing conditions. Figure 6.10 is an Eh-pH diagram for the stability field for chromous hydroxide. Under some conditions chromate might react with ferrous iron to produce a chromous hydroxide precipitate (Robertson 1975).

$$\mathrm{CrO_4^{2-} + 3Fe^{2+} + 8H_2O \rightleftharpoons 3Fe(OH)_3 + Cr(OH)_3 + 4H^+}$$

In general the hexavalent chromium in groundwater is soluble and mobile and trivalent chromium will be insoluble and immobile. Industrial discharges of hexavalent chromium are common from metal-plating industries. This material may be quite mobile in groundwater. A hexavalent chromium spill on Long Island, New York, U.S.A., traveled more than 900 m (≈3000 ft) from a waste-discharge pond to a stream (Perlmutter, Lieber, and Frauenthal 1963). Hexavalent chromium from a natural source has been found in groundwater in Paradise Valley, Arizona, U.S.A. (Robertson 1975), and the Blacksmith Institute reports that groundwater containing 6.2 mg/L Cr (VI) was found in Kanpur, India (the Indian government limit is 0.05 mg/L) from tannery operations, potentially affecting 30,000 people. Popular attention was focused on groundwater pollution from hexavalent chromium in Hinkley, California, U.S.A., after it was dramatized in the 2000 film *Erin Brockovich*.

Chromium in groundwater is much more mobile in the aqueous Cr^{6+} phase than as Cr^{3+}. In a study of a three dimensional chromium plume in a glaciofluvial aquifer in Connecticut, Nikolaos et al. (1994) tested the sorbed chromium in the soil and the dissolved chromium in the groundwater. The mean soil concentration was 0.675 g/kg while 25 mg/L was dissolved in the groundwater. A mass balance calculation reveled that more than 99% of the mass of chromium was immobilized in the soil. This has important implications for groundwater remediation. The mobile chromium in the groundwater could be removed by pump and treat methods. However, if the geochemical equilibrium is upset and chromium is desorbed from the soil, then it would be very difficult to ever remove all of the chromium by pump and treat. As a part of a remedial investigation at a chromium spill site, one must determine how strongly the chromium is bound to the soil. Methods of extracting the dissolved portion without upsetting the equilibrium that binds the majority of the chromium to the soil must be developed.

FIGURE 6.10 Eh-pH diagram for chromium under standard conditions.



Source: Modified from F. N. Robertson. 1975. Hexavalent chromium in the ground water in Paradise Valley, Arizona. *Groundwater* 13:516–527. Used with permission.

Case History

Henderson (1994) investigated a chromium spill in the Trinity Sand aquifer near Odessa, Texas. He found that the mobile Cr^{6+} was being reduced to Cr^{3+} by ferrous iron (Fe^{2+}) and organic carbon. The trivalent chromium is then sorbed onto the soil surfaces which are coated with solid iron oxyhydroxides. The soil contained up to 5 g/kg and 95 to 99 percent was in the trivalent state. Prior to the initiation of the study, the chromium plating operation had ceased operations, so that the source of hexavalent chromium ended. Over the course of the study, the plume of groundwater contaminated with Cr^{6+} stopped growing, and even began to shrink (Figure 6.11). The cause of this degradation is the reduction of the Cr^{6+} to Cr^{3+} which forms chromium hydroxide ($CrOH_3$) and its subsequent sorption onto the soil.

The calculated half life of the chromium was 2.5 years. The reduction in dissolved hexavalent chromium mass in the aquifer is illustrated in Figure 6.12. The shaded area represents observed conditions at four different sampling events. The curved line is a first order reduction with the 2.5 year half life.

With the transformation of dissolved to solid chromium as a function of time, the groundwater in the aquifer is undergoing natural remediation. Computer modeling of the plume resulted in a diminution of the dissolved Cr^{6+} below a 100 µg/L drinking water standard by no later than the year 2006 (Figure 6.13). Operation and maintenance at the site were still ongoing in 2017.

6.8.6 Cobalt

Cobalt occurs with valence states of +2 and +3. In the Eh and pH range of natural waters, only the +2 valence state is stable. It is thought that cobalt can coprecipitate or be absorbed by manganese and iron oxides. Cobalt carbonate has a solubility product of 10^{-10}. At a pH of 8.0 with 100 mg/L of carbonate, the equilibrium solubility of cobalt is 6 µg/L (Hem, 1985). The solubility product of cobalt sulfide is very low, $10^{-21.3}$. Virtually no cobalt would be in solution in a reducing environment. Radioactive cobalt is a waste product of certain defense activities (Means, Crerar, and Duguid 1978). Cobalt occurs in nature as smaltite ($CoAs_2$), and cobaltite ($CoAsS$). In the United States, stable cobalt has been identified at 426 of the 1,636 current or former National Priorities List (NPL) sites, whereas radioactive cobalt has been found at 13 sites (ATSDR 2015).

6.8.7 Nickel

This metal occurs in aqueous solutions in the +2 valence state. Nickel ores include a variety of minerals, consisting of nickel, antimony, sulfur, and arsenic: $NiSb$, $NiAs_2$, $NiAsS$, and $NiSbS$. Nickel carbonate is more soluble than cobalt carbonate ($K_{sp} = 10^{-6.9}$), whereas the sulfide has a similar solubility ($K_{sp} = 10^{-19.4}$). Nickel is widely used in industry.

6.8.8 Molybdenum

Molybdenum occurs as the ore mineral molybdenite, MoS_2. The most common oxidation states are +4 and +6. Under oxidizing conditions the Mo^{6+} state dominates. Below pH 1.8 one finds H_2MoO_4 (aqueous). Between pH 1.8 and pH 5.3, $HMoO_4^-$ occurs, whereas above pH 5.3 the molybdate ion, MoO_4^{2-}, is stable. If ferrous iron is present, ferrous molybdate ($FeMoO_4$) presents a possible solubility control, since this has a solubility product of $10^{-10.45}$ at a pH range of 5.3 to 8.5 (Hem 1977). Molybdenum may also sorb onto amorphous ferric hydroxide (Kaback and Runnels 1980). The solubility product of calcium molybdate, $CaMoO_4$, is $10^{-8.7}$ (Hem 1985). Molybdenum is used as an alloy in steel and as an additive to lubricants. Waste sources include mining and smelting of ore.

6.8.9 Copper

Copper occurs in either a +1 or a +2 valence state. Dissolved copper species in water include Cu^{2+}, $HCuO_2^-$, CuO_2^{2-}, and Cu+. Cupric copper and ferrous iron can undergo an oxidation-reduction:

$$2Cu^{2+} + 2Fe^{2+} + 7H_2O \rightleftharpoons Cu_2O + 2Fe(OH)_3 + 8H^+$$

Both cupric and cuprous sulfide have very low solubility products. Copper concentrations can be very high in acid mine drainage from metal mines, up to several hundred milligrams per liter. Copper can be leached from copper water-supply pipes and fixtures, especially by waters that have a pH of less than 7 (Hem 1985).

6.8.10 Silver

Silver, a rare element, is widely used in industry. It occurs in the +1 valence state. Silver chloride, AgCl, has a solubility product of $10^{-9.7}$, which limits the solubility of silver in waters with chloride ion. Silver can also be naturally reduced to the metallic state by ferrous iron:

$$Ag^+ + Fe^{2+} + 3H_2O \rightleftharpoons Fe(OH)_3 + Ag + 3H^+$$

Silver sulfide has a low solubility. Thus, in water with chloride, iron, and sulfur present, stable solid forms of silver occur over the entire Eh-pH field (Hem 1977). As a result, there is very little soluble silver in natural waters.

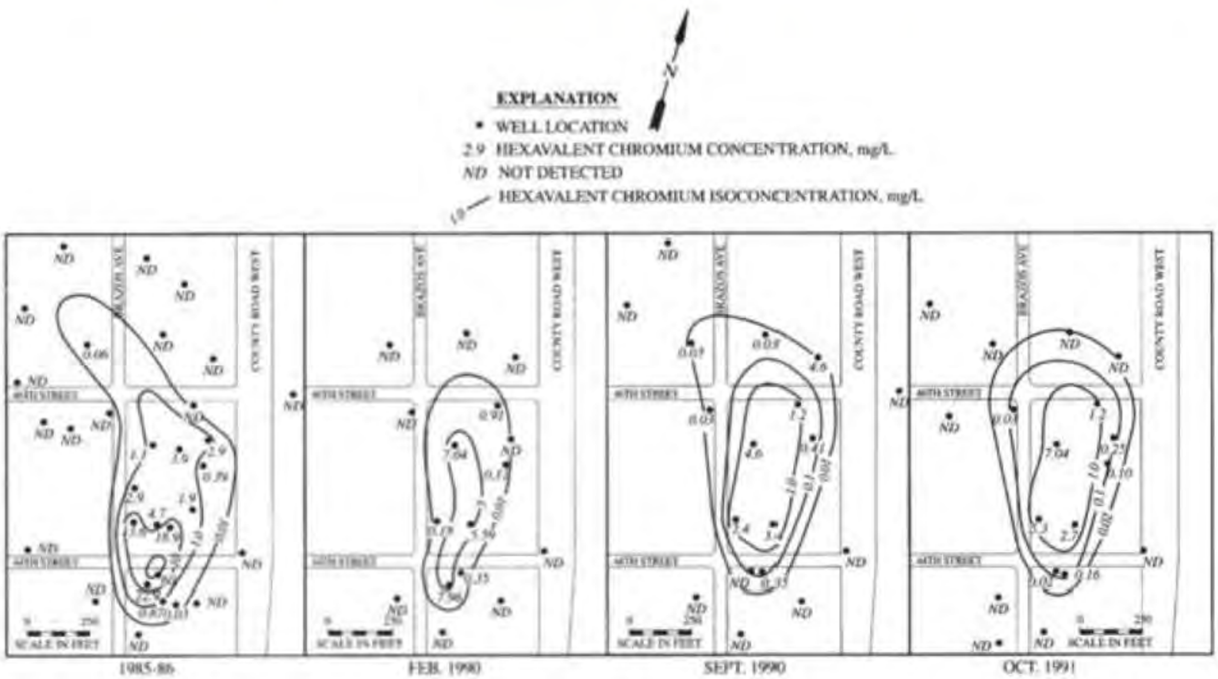
6.8.11 Zinc

Zinc is a fairly common metal and is extensively used in metallurgy and as a pigment, zinc oxide, which is often worn on the noses of lifeguards and other people in the sun. It occurs in the +2 valence state. Zinc carbonate has a rather low equilibrium constant, 10^{-10}, which would limit the solubility at pH ranges where the carbonate ion predominates. In a pH range of 8 to 11 and with 610 mg/L of HCO_3^-, there should be less than 100 μg/L of dissolved zinc (Hem 1985).

6.8.12 Cadmium

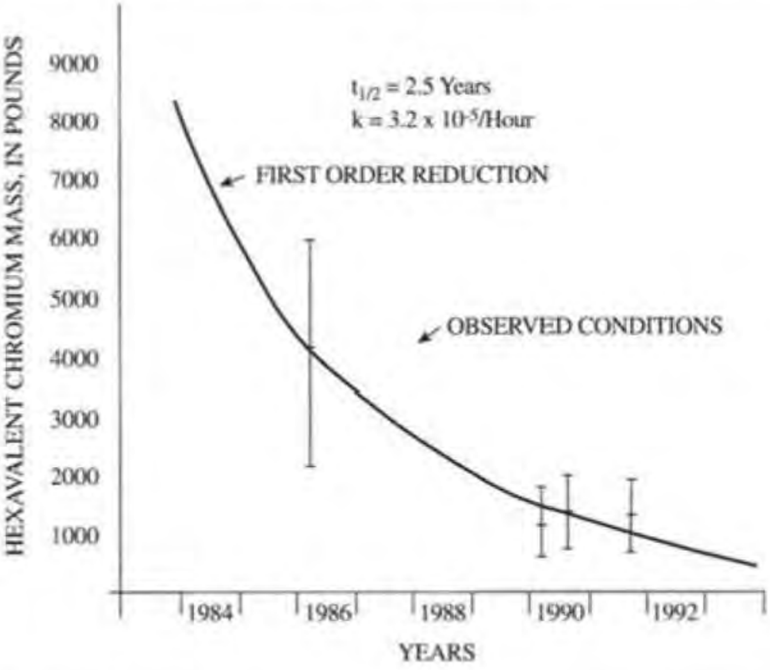
Cadmium has a very low maximum contaminant level (MCL) in drinking water, 4 μg/L, due to its toxicity. It exists in aqueous solution in the +2 valence state. Cadmium carbonate has a very low solubility product, $10^{-13.7}$. Although this could serve as a control on solubility under some conditions, cadmium can be mobile in the environment. On Long Island, New York, a metal-plating waste containing cadmium and chromium traveled about 3000 ft in a shallow aquifer (Perlmutter, Lieber, and Frauenthal 1963). Cadmium has been implicated in an outbreak of a disease in Japan resulting in a softening of the bones of the victims that resulted in extreme bone pain.

FIGURE 6.11 Shrinkage of the maximum extent of an observed plume of Cr^{6+} with time.



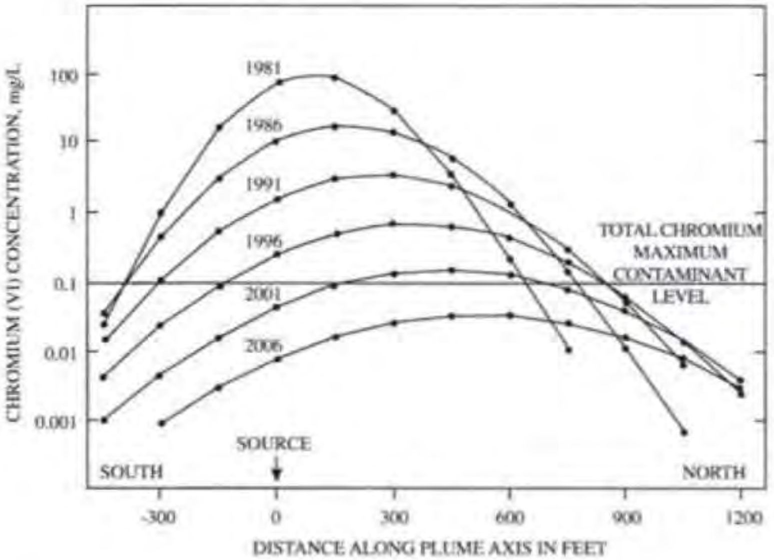
Source: T. Henderson. 1994. Geochemical reduction of hexavalent chromium in the Trinity Sand aquifer. *Groundwater* 32:477–486. Used with permission.

FIGURE 6.12 Reduction of the dissolved mass of Cr^{6+} with time.



Source: T. Henderson. 1994. Geochemical reduction of hexavalent chromium in the Trinity Sand aquifer. *Groundwater* 32:477–486. Used with permission.

FIGURE 6.13 Result of fate and transport modeling of concentration of Cr^{6+} along the axis of the plume.



Source: T. Henderson. 1994. Geochemical reduction of hexavalent chromium in the Trinity Sand aquifer. *Groundwater* 32:477–486. Used with permission.

The cadmium was traced to rice and soybeans grown in soil contaminated by airborne cadmium that came from a nearby lead-and zinc-smelting operation (Emmerson 1970).

6.8.13 Mercury

Mercury has the lowest MCL for any inorganic chemical, 2 μg/L. It is considered to be very toxic. It has been known to concentrate in the food chain, especially in fish. Several outbreaks of mercury poisoning have been confirmed in Japan. Local discharges of mercury from industrial processes into surface-water bodies resulted in high mercury levels in fish. Inhabitants of fishing villages ate fish up to three times a day. Mortality of those affected was about 40%, and the poisoning was passed to unborn babies by apparently healthy mothers (Waldbott 1973). Mercury occurs as a metal and in the valence states +1 and +2. Most of the inorganic mercury compounds have a low solubility. The solubility product of Hg_2Cl_2 is $10^{-17.9}$, and for HgS it is about 10^{-50}. Under most natural conditions there is little soluble inorganic mercury. However, methane-generating bacteria can convert metallic mercury to organic forms such as methyl mercury, $HgCH_3^+$. The monomethyl mercury ion is soluble in water. Bacteria can also produce dimethyl mercury, $Hg(CH_3)_2$, which is volatile. Other organic forms of mercury, such as ethylmercuric chloride (C_2H_5HgCl), are manufactured and used as fungicides.

6.8.14 Lead

Lead occurs in aqueous solution as Pb^{2+} and in various hydroxides. Various lead compounds have solubility products that indicate that under the right Eh-pH conditions, lead solubility would be limited in natural waters: $PbCl_2$, $K_{sp} = 10^{-4.8}$; PbF_2, $K_{sp} = 10^{-7.5}$; $PbSO_4$, $K_{sp} = 10^{-7.8}$; $PbCO_3$, $K_{sp} = 10^{-13.1}$ and PbS, $K_{sp} = 10^{-27.5}$. Lead and the other metals are cations that can be expected to undergo cation and exchange with clays. Hence, the mobility of lead in groundwater is limited. Lead is present in nature as a trace element. In two different studies soils in uncontaminated areas were reported to contain 17 μg of lead per gram of soil (μg Pb/g) (Nriagu 1972) and 29 μg Pb/g (Ure and Berrow 1972). However, there are a number of anthropogenic sources of lead, including mining and smelting, paint, use of sewage sludge as a soil conditioner, lead arsenate pesticides, and leaded gasoline. Urban areas especially have much higher levels of lead in the soil due primarily to paint flaking from buildings and burning of leaded gasoline (Davis 1990). A study of lead in soils near highways in the Minneapolis-St. Paul, USA, area revealed concentrations ranging from 128 to 700 μg Pb/g (Singer and Hanson 1969). A study in California, U.S.A. found that lead in soil decreased with distance from a freeway which ran through a rural area, with 118 μg Pb/g found 15 meters from the expressway and 85 μg Pb/g as much as 362 meters away (Page et al. 1971). Lead additives were used as anti-knock compounds in gasoline, but are now restricted or banned in many parts of the world.

Elevated lead is also found in soil around lead smelters. Davies (1990) estimates that in the immediate area of a well established lead smelter (1 to 3 km away), lead in soil is likely to be on the order of 1500 μg Pb/g. In a study conducted in southeastern Missouri, USA, the investigators were able to distinguish lead from automobile exhaust from lead from smelter activities on the basis of the ratio of stable lead isotopes, $^{206}Pb/^{204}Pb$ (Rabinowitz and Wetherill 1972). In that study they found lead in soil near smelters averaging 2600 μg Pb/g and near highways averaging 270 μg Pb/g.

In general urban soils have higher lead content than rural soils. In a major study of metals in urban soils in Great Britain a total of 4,126 lawns were tested, with a geometric mean lead content of 266 μg Pb/g and a range of thirteen to 14,100 μg Pb/g (Culbard et al. 1988). In London a total of 578 samples had a geometric mean lead content of 654 μg Pb/g.

Soluble lead is absorbed by soils, and its mobility is limited. The two most important factors in determining the amount of lead that will be sorbed by soil are the pH and the cation exchange capacity (CEC) of the soil (Zimdahl and Skogerbe 1977). This relationship can be described by an equation, with the amount of lead sorbed per gram of soil represented by N^*:

$$N^*_{(\mathrm{mol/gm})} = 2.81\times10^{-6}\mathrm{CEC}_{(\mathrm{meq/100\,g})} + 1.07\times10^{-5}\mathrm{pH} - 4.93\times10^{-5}$$

The above equation shows that with a pH greater than 4.61 the amount of lead sorbed by the soil increases and that below a pH of 4.61, it decreases. The cation exchange capacity of a soil is dependent upon the amount and type of clay in the soil and the amount of soil organic matter. Lead absorption is due to precipitation of the carbonate, fixation on organic matter, or sorption by hydrous oxides of iron and magnesium. Griffin and Shimp (1976) demonstrated that the sorption capacity of a clay for lead at a pH of 5.0 was much greater than at a pH of 4.0.

Because of the high affinity of soil for lead, the metal tends to accumulate in the upper few centimeters of soil. In a study of heavy metal mobility in soils near a zinc smelter, lead was found to be concentrated in the upper 10 cm of the soil (Scokart et al. 1983). This was due to the extremely low mobility of lead in soil. The reason that urban soils have such high lead levels is twofold. First, there are more sources of lead. But more important is the fact that the lead in the soil is so immobile that it continues to accumulate. In a study of trace metals in virgin agricultural soil profiles in Canada, Wright and others (1955) found lead to be more concentrated in the upper part of the soil profile. The lead was assumed to come from the weathering process and was concentrated in the zone where leaching was the most prevalent. This is further evidence for the very low mobility of lead in the environment.

There is one potential pathway for lead migration. If lead is sorbed onto colloidal-sized metal hydroxides, and the hydroxide moves through an aquifer as a colloidal particle, then the lead would also move. This would show up as lead in total metals analysis, which is run on an unfiltered sample. The colloidal particles, which may impart turbidity to the sample, would be digested and any sorbed lead liberated in the analysis. Colloidal-sized lead particles could also migrate with groundwater and be detected with the total lead analysis.

6.8.15 Rare Earth Elements

Rare earth elements (REEs) are increasingly important materials for modern technologies and can be found in groundwater. Although REE concentrations in groundwater can be low, they are used in investigations as tracers to indicate water movement and source, and importantly have associated radioactive pollutants in REE mining waste. There are 17 REEs, but the name "rare" is misleading as some (e.g., cerium) can be relatively abundant in the earth's crust. REE mining activity is rapidly expanding as are the economic uses of REEs. For example, REEs are used in cellular phones, laptop computer hard drives, automobile airbags and ABS brakes, medical magnetic resonance imaging (MRI), hybrid car batteries, wind turbine generators, plasma color televisions, satellite components, and communications equipment, to name a few applications. REEs have been shown to be useful in tracking and tracing groundwater (Johannessonn et al. 1997; Kreamer et al. 1996; Johannessonn 2006), and radioactive elements of uranium and thorium are commonly found in slurry tailing from REE mining.

6.9 Radioactive Isotopes

6.9.1 Introduction

Certain isotopes of elements undergo spontaneous decay, resulting in the release of energy and energetic particles and consequent formation of different isotopes. Some of these radioactive isotopes are naturally occurring and others are created by the bombardment of the Earth by cosmic radiation. Humans have created nuclear isotopes through the detonation of nuclear weapons and the construction of nuclear reactors. Table 6.6 lists the sources of environmentally important isotopes.

Radionuclides emit ionizing radiation–alpha particles, beta particles, and gamma rays–when they decay. An alpha particle is a helium nucleus with atomic mass 4 and atomic number 2. A beta particle is either a negative electron or a positron (positive electron). Gamma radiation consists of electromagnetic radiation similar to X-rays but more energetic (i.e., it has a shorter wave length). Gamma radiation is more destructive to tissue than X-rays. The primary effect of these particles is to produce ions, hence the name ionizing radiation. Alpha particles do not penetrate very far into matter due

TABLE 6.6 Sources of environmentally important radioactive isotopes.

Source	Radionuclides
Naturally occurring	^{40}K , ^{222}Rn, ^{226}Ra, ^{230,232}Th, ^{235,238}U
Cosmic irradiation	^{3}H, ^{7}Be, ^{14}C, ^{22}Na
Nuclear weapons tests	^{3}H, ^{90}Sr, ^{137}Cs, ^{239,240}Pu
Mining waste—uranium, phosphate, coal	^{222}Rn ^{226}Ra, ^{230,232}Th, ^{235,238}U
Industrial wastes—e.g., nuclear power plants, weapons manufacturing, research and medical waste	^{59,63}Ni, ^{60}Co, ^{90}Sr, ^{93,99}Zr, ^{99}Tc, ^{107}Pd, ^{129}I, ^{137}Cs, ^{144}Ce, ^{151}Sm, ^{152,154}Eu, ^{237}Np, ^{239,240,242}Pu, ^{241,243}Am

Source: G. W. Gee, D. Roi, and R. J. Serne. 1983. Mobility of radionuclides in soil. In D. W. Nelson et al. (ed.) *Chemical Mobility and Reactivity in Soil Systems*, 203. (Madison, WI: Soil Science Society of America Spec. Publ. 11, 1983).

to their large size, but they produce a lot of ions along their short path. Beta particles penetrate to a greater depth but produce fewer ions per unit path length.

Radionuclide concentrations can be reported in terms of their mass per volume concentration (e.g., milligrams per liter). However, they are more frequently reported in terms of a standard unit of radioactivity, the **curie** (Ci). A curie is 3.7×10^{10} disintegrations per second. In water we use the **picocurie** (pCi), which is 1×10^{-12} Ci, or 3.7×10^{-2} disintegrations per second. In the SI system the unit of radioactivity is the **becquerel** (Bq), which is 1disintegration per second.

Radiation doses are measured in terms of **rads**, which are a measure of the absorption by the body of ionizing radiation of any type. A rad is equivalent to 100 ergs of energy from ionizing radiation absorbed per gram of soft tissue. In the SI system the unit of dose is a **gray** (Gy), which is equal to 100 rads.

The effect of ionizing radiation depends upon the type of particle and the body tissue with which it interacts. Therefore, the absolute measurement of dose must be converted to a **dose equivalent**. The unit of dose equivalent is the **rem**. Rads are converted to rems by multiplying by a factor that depends upon the type of ionizing radiation and its biological effect. For example, with gamma radiation the factor is 1and a rad is equal to a rem. In the SI system the unit of dose equivalent is the **seivert** (Sv), and it is equal to a gray times the dose factor. A seivert is 100 rem.

6.9.2 Adsorption of Cationic Radionuclides

The cationic radionuclides may be subjected to ion exchange and other processes that sorb the radionuclide onto mineral or organic surfaces in the soil. The following transition metals and lanthanides have large distribution coefficients and hence low mobilities in waters that are in the neutral range: ^{60}Co, ^{59}Ni, ^{63}Ni, ^{65}Zn, ^{93}Zr, ^{107}Pd, ^{110}Ag, ^{114}Ce, ^{147}Pm, ^{151}Sm, ^{152}Eu, and ^{154}Eu. Many of them do not desorb significantly. The degree of sorption is strongly related to the pH of the solution. Insoluble metal hydroxides may also be formed. Technetium (Tc) solubility depends strongly upon the Eh of the solution, because under oxidizing conditions it forms the soluble pertechnetate ion (TcO_4^-) (Gee, Rai, and Serne 1983).

^{90}Sr, ^{137}CS, and ^{226}Ra undergo cation exchange in a fashion similar to other exchangeable cations, such as Ca^{2+} and Mg^{2+}. Thorium and lead also have high distribution coefficients and limited mobility in neutral to alkaline soil. Lead is sorbed on hydrous oxides of iron, aluminum, and most likely manganese. Thorium hydroxides are of very limited solubility (Gee, Rai, and Serne 1983).

6.9.3 Uranium

Uranium occurs primarily as ^{238}U, with ^{235}U being much more rare. One of the disintegration products of ^{238}U is ^{226}Ra. This decay series ends with ^{206}Pb, a stable isotope. ^{238}U can also degrade to ^{234}U. The $^{234}U/^{238}U$ ratio is useful in tracking and dating groundwater (see Chapter 8). ^{238}U has a very long half-life, 4.5×10^9 years, which indicates that it is not very radioactive. The ^{235}U isotope can decay to form ^{223}Ra.

The chemistry of dissolved uranium is somewhat complex (Giridher and Langmuir 1991; Langmuir 1978). It has three valence states, +4, +5, and +6. Uranium can undergo oxidation-reduction reactions such as oxidation from the +4 to the +6 state:

$$U^{4+} + 2H_2O \rightleftharpoons UO_2{}^{2+} + 4H^+ + 2e^-$$

In a system with just uranium and water, stable species include (1) +4 valence: U^{4+} UOH^{3+} , and (2) +6 valence: UO_2^{2+} UO_2H^+ $(UO2)_3(OH)_5$ + and $(UO2)_3(OH)_7$-. The stability fields for this ions and precipitates are shown in Figure 6.14 for an aqueous solution with a total uranium activity of 10^{-6} mol/L The U(6+) species has a tendency to from a complexes with a wide variety of inorganic anions, including carbonate, hydroxide, phosphate, fluoride, and sulfate. This can be illustrated with an Eh-pH diagram of the same 10^{-6} mol/L solution of U but in contact with carbon dioxide at a partial pressure of 10^{-2} atm. This is represented by Figure 6.15. In Figure 6.14 the UO_2^{2+} formed a series of complexes with OH^-, starting with UO_2OH^+, at a pH above about 5.2. With carbon present, as in Figure 6.15, UO_2^{2+} can form a series of carbonate complexes that replace the hydroxyl complexes.

The soluble complexes of oxidized uranium depend upon the pH of the water. Most natural water contains fluoride, phosphorus, carbon dioxide, and sulfur. Figure 6.16 shows the distribution of uranyl complexes for a groundwater under standard conditions with $P_{CO2} = 10^{-2.5}$ atm, $F^- = 0.3$ mg/L, $Cl^- = 10$ mg/L, $so_4^{2-} = 100$ mg/L, and $P0_4^- = 0.1$mg/L. In different pH ranges the most prevalent stable species include

$$UO_2^{2+}, UO_2(HPO_4)_2^{2-}, UO_2(CO_3)_2^{2-}, \text{and } UO_2(CO_3)_3^{4-}.$$

If reduced species of iron or sulfur are present, they could reduce U(6+) to U(4+) and precipitate the nearly insoluble mineral uranite, UO_2 This reduction could occur by oxidation of HS^- to SO_4^{2-}:

$$4UO_2(CO_3)_3{}^{4-} + HS^- + 15H^+ \rightleftharpoons 4UO_2(s) + SO_4{}^{2-} + 12CO_2(g) + 8H_2O$$

The same reduction could be accomplished by oxidation of ferrous iron to ferric hydroxide:

$$UO_2(CO_2)_3{}^{4-} + 2Fe^{2+} + 3H_2O \rightleftharpoons UO_2(s) + 2Fe(OH)_3 + 3CO_2$$

Because sulfur and iron are common in groundwater systems, under reducing conditions one could expect the formation of uranite, which would remove uranium from solution. Figures 6.14 and 6.15 show the stability field for uranite ($U0_2$). In the has a very low solubility. The primary thorium ore is monazite, which contains oxides of thorium, phosphorus, and the rare earths yttrium, lanthanum, and cerium.

The mobility of thorium is greatly enhanced if ligands are present to form complexes. Figure 6.20 shows the inorganic thorium complexes that form as a function of the pH of the solution. The solution contains 0.3 mg/L F^-, 10 mg/L Cl^-, 100 mg/L SO_4^{2-} and 0.1mg/L PO_4^{2-}. It can be seen from this figure that the most abundant aqueous species in order of increasing pH are $Th(SO_4)_2^0$,ThF_2^{2+} $Th(HPO_4)_2^0$, $Th(HPO_4)_3^{2-}$ and $Th(OH)_4^0$ However, the mobility of thorium complexes formed by organic ligands such as EDTA and citric acid are much greater than those formed by inorganic ligands (Langmuir and Herman 1980).

Adsorption of dissolved thorium increases with increasing pH above pH 2. The sorption of thorium onto clays, oxides and soil organic matter is nearly total by a pH of 6.5. Strongly complexing organic ligands such as EDTA can retard sorption or even promote desorption (Langmuir and Herman 1980). Thorium in natural waters and soil should be nearly immobile due to the low solubility of the minerals and the strong tendency for dissolved forms to be sorbed only by clays, mineral oxides, and soil organic matter.

6.9.5 Radium

Radium occurs naturally in four isotopes: ^{223}Ra, 226Ra and ^{228}Ra.^{232}Th decays into both ^{228}Ra and ^{224}Ra, whereas ^{235}U decays to ^{223}Ra and ^{238}U disintegrates to ^{235Th}, which in turn decays to ^{226}Ra. One isotope, ^{226}Ra, has a much longer half-life than any of the others, 1599 years. Because of their short half-lives, the radium isotopes are strongly radioactive (Hem 1985).

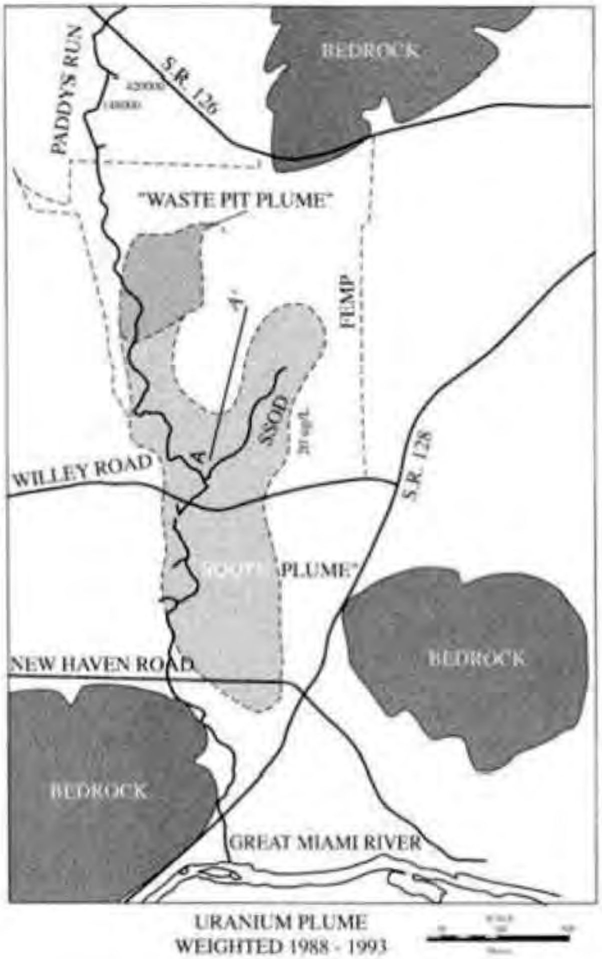
Knowledge of the aqueous chemistry of radium is summarized in IAEA (2014). It is reportedly similar in chemical behavior to barium (Hem 1985) and calcium (Kathren 1984). It is more soluble than uranium or thorium and can be bioconcentrated by plants (Brazil nuts have an especially high radium content). Radium can be strongly exchanged in the cation exchange series. According to Kathren (1984), the cation exchange sequence for soils is

$$Sr^{2+} < Ra^{2+} < Ca^{2+} < Mg^{2+} < Cs^{2+} < Rb^{2+} < K^+ < NH_4^+ < Na^+ < Li^+$$

^{228}Ra has a much shorter half-life, (5.8 yr) than ^{226}Ra. However, its parent, ^{232}Th, is more abundant in nature than ^{238}U, the parent of ^{226}Ra. As a result, both isotopes are found in groundwater. The U.S. EPA has proposed MCLs of 20 pCi/L for both ^{226}Ra and ^{228}Ra (Federal Register, July 18, 1991). Wells with high radium levels in groundwater have been discovered to be concentrated in two areas of the United States: the Piedmont and coastal plain of the Middle Atlantic states and the upper Northwestern states of Minnesota, Iowa, Illinois, Missouri, and Wisconsin (Hess et al. 1985). Table 6.7 summarizes the distribution of ^{226}Ra and ^{228}Ra in the Atlantic coastal plain and Piedmont region.

The radium content of groundwater is a function of the rock type of the aquifer. Igneous rocks, such as granites, contain the highest proportion of uranium and thorium, the parent isotopes of radium. Granitic rock aquifers and sands and sandstones derived from the weathering of granites have the potential to have high radium. Phosphate rock is also very high in uranium. Radium is not only a problem that is naturally occurring,

FIGURE 6.17 Composite plume of total dissolved uranium >0.20 μg/L for the period 1988 to 1993.



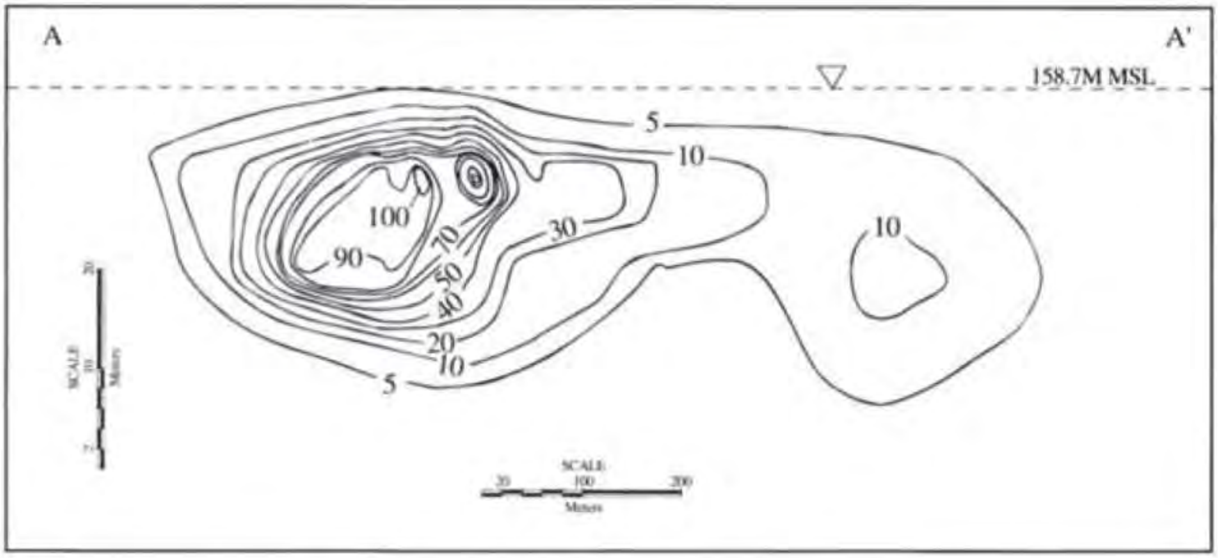
Source: W. C. Sidle and P. Y. Lee. 1996. Uranium contamination in the Great Miami Aquifer at the Fernald Environmental Management Project, Fernald Ohio. *Groundwater* 34:876–882. Used with permission.

Table 6.7 Distribution of 226Ra and 22BRa by aquifer type in the Atlantic coastal plain and Piedmont provinces.

Aquifer Type	Number of Samples	Ra−228 (pCi/L) Geometric Mean	Ra−228 (pCi/L) Range	Ra−226 (pCi/L) Geometric Mean	Ra−226 (pCi/L) Range
Igneous (acidic)	42	1.39	0.0–22.6	1.8	0.0–15.9
Metamorphic	75	0.33	0.0–3.9	0.37	0.0–7.4
Sand	143	1.05	0.0–17.6	1.36	0.0–25.9
Arkose	92	2.16	0.0–13.5	2.19	0.0–23.0
Quartzose	50	0.27	0.0–17.6	0.55	0.0–25.9
Limestone	16	0.06	0.0—0.2	0.12	0.0—0.3

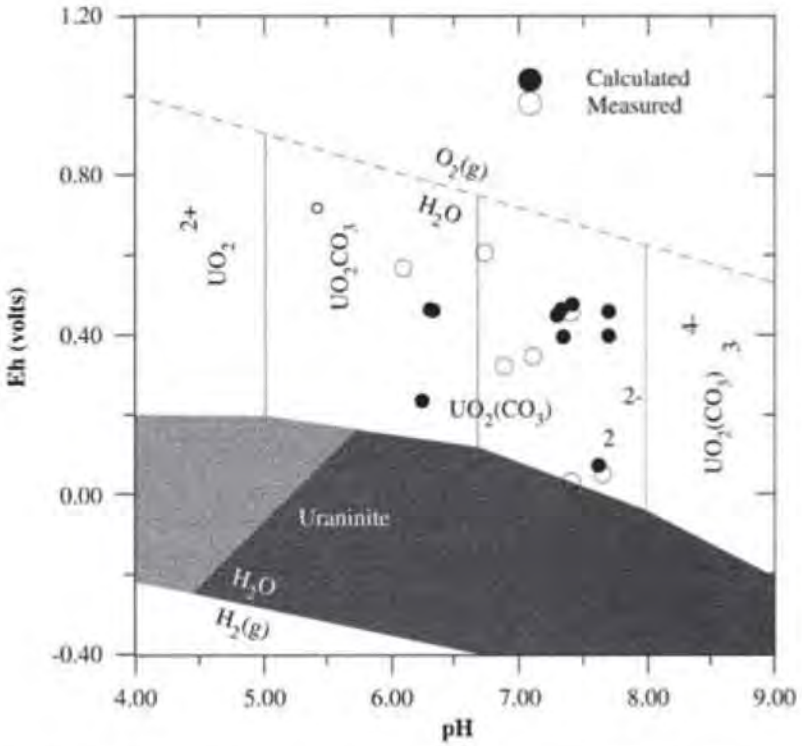
Source: C. T. Hess, J. Michel, T. R. Horton, H. M. Prichord, and W. A. Coniglio, "The occurrence of radioactivity in public water supplies in the United States," *Health Physics* 48 (1985):553–86.

FIGURE 6.18 Longitudinal profile of total dissolved uranium along line A – A′ from Figure 6.17.



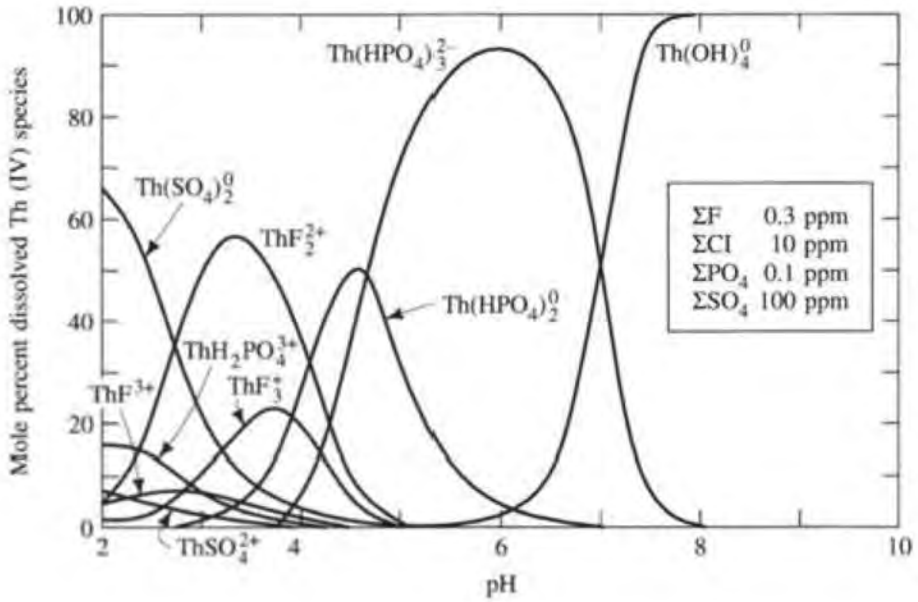
Source: W. C. Sidle and P. Y. Lee. 1996. Uranium contamination in the Great Miami Aquifer at the Fernald Environmental Management Project, Fernald Ohio. *Groundwater* 34:876–882. Used with permission.

Figure 6.19 Measured and calculated redox potential for the UO_2^{2+}/U^{4+} pair plotted on the $\Sigma U = 10^{-6}$ stability field.



Source: W. C. Sidle and P. Y. Lee. 1996. Uranium contamination in the Great Miami Aquifer at the Fernald Environmental Management Project, Fernald Ohio. *Groundwater* 34:876–882. Used with permission.

Figure 6.20 Distribution of thorium complexes as a function of pH under standard conditions for an aqueous solution containing 0.3 mg/L F^-, 10 mg/L Cl^-, 100 mg/L SO_4^{2-}, and 0.1 mg/L PO_4^{2-}.



Source: D. Langmuir and J. S. Herman. 1980. The mobility of thorium in natural waters at low temperatures. *Geochemica et Cosmochimica Acta* 44:1753–1766. Used with permission.

but there are localized areas of radium contamination from industrial operations. These are associated with uranium mill tailings as well as facilities where radioluminescent paints were prepared and used. For example, from World War I up until 1968 wrist watches with radium dials that glowed in the dark were sold in the United States.

6.9.6 Radon

There are several isotopes of radon, but ^{222}Rn is the only one that is important environmentally. The other isotopes have half-lives of less than 1 min. The half-life of ^{222}Rn is 3.8 days. ^{222}Rn is produced by the decay of ^{226}Ra, so that it is associated with rocks that are high in uranium. Radon can be associated with water that is low in dissolved ^{226}Ra, because it comes primarily from the decay of the radium in the rock. Radon is a noble gas and does not undergo any chemical reactions, nor is it sorbed onto mineral matter. Radon is lost from water by diffusion into the atmosphere and by radioactive decay through a series of short-lived daughter products to ^{210}Pb, which has a half-life of 21.8 yr.

The EPA has proposed an MCL standard of 300 pCi/L for radon in drinking water (Federal Register, November 2, 1999). However, there is also a health concern for excessive radon accumulation in homes. Radon can enter homes through emanations from the soil as well as by diffusion from tap water with a high radon content.

Owners of private water systems are most at risk from radon in drinking water. Public water-supply systems normally have storage facilities to supply water during fires. The residence time for the water in these facilities allows the radon to both diffuse and decay. Private water systems rely upon wells and usually only have a very small storage facility used to maintain pressure.

8

Site Characterization—Groundwater and Soil Monitoring

8.1 Introduction

Characterization of a potentially contaminated site involves field and laboratory analysis of subsurface properties, with a goal of building a conceptual model of contaminant source strength and configuration, and pollutant movement and transformation with time and space. This, in turn, is done to optimize monitoring strategies, and develop advantageous and cost effective remedial solutions.

The process of characterization begins with identifying the goals of characterization and remediation, and these goals can widely vary. Site characterization approaches will be quite different if the overall goal is to identify parties responsible for pollution, versus a goal of protecting public health, versus a goal of maintaining a vibrant groundwater dependent ecosystem. Further, a site can have several prioritized goals and not just one. Objectives are often linked, for example, one objective might be to minimize costs by requiring a thorough (and perhaps costly) site characterization in order to reduce potentially higher remediation costs by strategically targeting pollutants. There are many different site characterization methodologies including phased or progressive approaches and adaptive management techniques. At a site where very little is known about the nature and extent of subsurface contamination, often a first sampling step is collection and analysis for a broad range of potential contaminants, to be narrowed and focused based on the findings of those early surveys.

It must be emphasized that each site is unique and should not be addressed in a "one size fits all" or "we did it this way at the last site" boilerplate approach. Some of the seemingly smallest changes in geologic heterogeneities at different sites can radically alter subsurface fluid flow, and if unrecognized can cause inappropriate assumptions to be made and incorrect approaches to be followed. Likewise, site-specific physical, human-made features that protrude into or affect the subsurface (e.g., building footings, buried pipeline trenches backed-filled with gravel or other non-native material, groundwater pumping, surface irrigation or paving, application of chemicals at the ground surface, chronic and slow leaks versus massive leaks) all can alter how pollutants change their distribution, phase, form, and potential threat. An underlying note of caution is that the data that monitoring provides is not always representative of the complete hydrogeological picture or demonstrates contaminant distribution. Not accounting for these unique properties at each site, or blindly assuming that selected monitoring data is broadly representative of actual field conditions, can cost huge sums in misspent money, useless monitoring, ineffective remediation, lost time, and misstated risks (Nielsen 2005).

There are some general perspectives and overall guiding principles regarding monitoring and site characterization that are helpful. They include the following:

1. Resources spent on proper and thorough site characterization typically save many times their investment in reduced remedial costs.
2. Incautious monitoring installation and practices can make the original environmental problem worse by allowing cross-contamination and short-circuiting of contaminant migration.
3. It is standard to have well-defined goals for characterization and remediation before embarking on site activities.
4. It is very helpful to calculate a good mass balance of contaminants early on, including an estimate (or range of estimates) in source mass, amount retained in vadose zone, amount reaching the water table, mass dissolving into water, mass volatilizing into the gaseous phase, amount sorbing onto soils, mass transforming and/or chemically or biologically degrading, and other sources and sinks of contaminant mass.
5. Typically assessment should begin with noninvasive methods (methods that do not appreciably disturb the subsurface at a site) in order to optimize subsequent invasive methods (such as monitoring well installation).
6. Employing an "outside-in" approach where possible is advantageous to reduce equipment contamination or to prevent contaminant spreading, (e.g., drilling monitoring wells first in areas suspected of low contamination rather than "hot spots," or the practice of sampling wells deemed to be cleanest with low contamination first to reduce the possibility of cross contamination).
7. Phased approaches have benefits in allowing adjustment in monitoring strategies as more information is learned.
8. Consider early/interim remedial action as monitoring and monitoring plans are progressing (beyond just typical emergency response actions to immediate threats). Actions which are taken as monitoring plans are being completed can include: providing early source isolation, plume containment, and extraction of nonaqueous phase liquids to reduce their propensity to migrate.

There are a selection of noninvasive, or minimally invasive techniques available for initial groundwater surveys at potentially contaminated sites, and these procedures are often followed by groundwater and soil sampling. For groundwater sampling, the more invasive methods of installing monitoring wells and collecting groundwater samples have been developed with the specific intention of obtaining a representative sample of water from an aquifer (FDEP 2008; Hughes and Aarons 2014; Aller et al. 1991; NUDLC 2012; Arnold et al. 2009). These monitoring well methods minimize the potential for the introduction of contaminants into the ground through the process of installing a monitoring well. Wells and sampling devices can be constructed of materials that have a minimum tendency to leach materials into and sorb compounds from the water sample. Groundwater samples can be collected in such a manner that dissolved gases are not lost or exchanged with the atmospheric gases. Soil samples can also be collected for classification and chemical analysis.

Various methods of collecting samples of soil water are also available, as are procedures for determining the location and nature of subsurface contamination. Soil gas sampling can be done to give an indication of areas where volatile organic compounds are contained in the soil or groundwater. Many other forensic approaches help with the determination of groundwater and contaminant travel times, source location and timing, contaminant transformations and phase changes, geological formations and structures, and potential risk.

Proper site characterization can transform understanding and advance the development of effective remedial strategies. Australian guidance defines the "sound science" associated with contaminated site characterization and development of robust site conceptual models as being based on "organized investigations and observations conducted by qualified personnel using documented methods and leading to verifiable results and conclusions" (NSW 2010).

8.2 Noninvasive Measures

At the beginning of a site characterization program, noninvasive methods are employed to understand the site without excessive perturbation of the subsurface. Although monitoring wells are usually an essential part of characterizing groundwater contamination, their installation can trigger vertical migration of pollutants, depending on the method of installation. A site characterization process typically begins with definition of objectives and a review of site specifics and history. Records of facility operations and inventories are investigated, contaminant handling practices at the site are looked into, drains and drywells are located, surface features and drainage patterns are reviewed, buried pipelines are identified, past and present employees may be interviewed, pertinent climatic data checked, existing local wells pinpointed along with associated groundwater quality data, and applicable law and regulations reviewed. As part of this process, facility records and manifests are analyzed to understand the possible mass of contaminants handled historically at the site. Agency and utility files, and regional geologic and hydrogeologic information are evaluated. An integral part of these undertakings is an initial site water balance and contaminant mass balance. Most of these undertakings are office related and not carried out directly on-site.

Air photo interpretation, surface geophysics, and quick soil and surface water survey and screening techniques are minimally invasive field techniques. Soil gas surveys are particularly useful for volatile compounds, and there are other noninvasive and informative practices useful in initial site assessment.

8.2.1 Interpretation of Aerial Photography and Remote Sensing

A review of site surface features, both present-day and historical, are easily accessible with the advent of widely available air photo libraries, such as National Aeronautics and Space Administration (NASA) World Wind and Google Earth. Many things pertinent to site characterization can be observed from visible aerial photography. This includes past and present site structures, roads and access points, possible soil staining or discoloration, the proximity of nearby creeks and streams, local wetlands and reservoirs and how these change with time, vegetative changes, urbanization, local erosion, industrial surface impoundments, and evaporation ponds. In tectonically active terrain, faults can sometimes be identified by observable surface lineaments. (Faults can be crucial to groundwater flow and contaminant movement in fractured terrain). Because of the replacement of film with digital imagery, the record of aerial photography has come to have a previously unrealized permanence. It should be noted that aerial photography displays a degree of radial distortion and without correction measurements of distance and topography are not accurate. Even so, aerial observation can provide better spatial resolution and geometric fidelity than many ground-based approaches.

The electromagnetic spectrum beyond visible light can also be quite helpful, as aerial photography provides broader spectral sensitivity than the human eye. Spectral bands or individual wavelengths can help identify many site activities. For example, near-infrared radiation (reflectance) can identify plant health, and thermal infrared (emitted spectra) can show heat sources on a property. Radar scanning can identify topographic expressions of subtle features like faults and folds often better than conventional satellite images. These radar techniques include Side-Looking Airborne Radar (SLAR) and LIDAR (a combination of the word "light" and "radar") that can identify ground uplift or subsidence, and define geomorphologic features. There are also airborne geophysical techniques that are noninvasive and help define the geological surroundings of a site. Although traditionally used for geologic resource and mineral assessment, aeromagnetic, radiometric, and gravity surveys can add important information to an understanding of field geological influences on contaminant travel.

8.2.2 The Use of Surface Geophysical Techniques for Site Characterization

Noninvasive surface geophysical techniques can advance site characterization in many ways, although some techniques are expensive, and natural and human-made surface features can interfere with their efficacy. American Standard Testing Methods' ASTM D6429-(2011)e1 is a standard guide for selection of surface geophysical methods, and Olhoeft (1992) provides a Geophysical Advisor Expert System to facilitate field decisions on appropriate geophysical methods.

Electromagnetic Surveys (EM) One surface geophysical method is an electromagnetic survey that measures the magnetic susceptibility of earth materials and their variation. An electromagnetic (EM) induction sensor can detect subsurface electrical conductivity dissimilarities, and therefore is good for locating lateral changes or discontinuities in soil or rock, and fluid filled fracture zones. These heterogeneities can be extremely important in subsurface contaminant movement, particularly for nonaqueous phase liquids (NAPLs). EM techniques can directly detect: burial trenches or pits containing drums or bulk wastes, electrically conductive plumes (particularly useful in coastal saltwater intrusion and saline landfill plumes), plume movement using time-series measurements, and utility pipes/cables (which may transport contaminants through their trench backfill and/or interfere with other geophysical techniques). Electrical conductivity variation can also be an indicator of NAPL presence.

Airborne electromagnetic surveys can explore large swaths of land, helping to delineate factors directly pertinent to contaminant hydrogeology such as large faults, paleochannels and shear zones with appreciable groundwater and/or clay gouge, and dissimilarities in the electrical conductivity of groundwater bodies. Helicopter transient electromagnetic surveys (TEM) can examine subsurface properties down to 200m depth, and have been used to identify contaminated landfill sites, model pollution and coastal hydrogeology, and optimize management of mining tailings facilities (Silvestri et al. 2009; Pellerin et al. 2010; Kirkegard et al. 2011; Christensen and Halkjaer 2014).

Direct Current Resistivity and Induced Polarization Another geophysical technique is a direct current resistivity survey that employs a constant electrical source using electrodes placed in the ground. The attenuation of voltage from between these electrodes (electrical resistance) allows calculation of depths to water tables or water-bearing horizons, freshwater/ saltwater interfaces, depth to bedrock, and stratigraphy at a site. Like EM techniques, direct current resistivity can identify electrically anomalous plumes and burial sites for bulk wastes and drums. Fencelines, pipelines, and other surface interferences can alter DC resistivity results. A related technique is induced polarization which measures the transient electrical response. This technique has been applied to locating subsurface NAPLs and tracking active or passive remediation, particularly for surfactants that might be injected for soil flushing cleanups (Personna et al. 2013; Magill 2009).

Time Domain Reflectometry Time Domain Reflectometry or TDR measures the relationship between the velocity that an electromagnetic wave moves through and between metal rods which are pushed into the ground, and the dielectric constant of the soil through which the wave propagates. This method has been used to estimate soil water content for many years, but many other applications for contaminated soil have been developed. For example, Olchawa and Kumor (2008) have used a soil's dielectric permittivity measured with TDR to measure the content of diesel oil in soil.

Magnetometry Magnetometry measures nonuniformities in the earth's magnetic field typically caused by buried tanks and drums made of ferrous material (iron and steel) and underground pipelines and utilities. Because many industrial sites have the potential to contain leaking tanks or pipes, these surveys can help locate problem areas. Even in the absence of leaking tanks and pipes, backfill surrounding underground tanks and pipes can be a conduit for some future pollutant flow and can be identified as a potential preferred pathway for fluid migration. Also, locating buried utility features is a critical step before drilling monitoring boreholes.

Seismic Surveys Reflective and refractive seismic techniques require an energy source such as a force striking the ground which generates low-amplitude waves through the earth to surface geophones that record the arrival of these waves. The time delay of wave arrival provides information that can help calculate subsurface stratigraphy, depths to both water table and bedrock, physical and elastic properties of subsurface formations, and lateral soil/rock discontinuities. Because pollution sources can either be pooled up above, or deflected by, subsurface layers, their identification is important in developing an accurate site conceptual model.

Ground Penetrating Radar (GPR) Ground penetrating radar (GPR) in optimal circumstances also can identify depth to water table and bedrock, stratigraphy, metallic and nonmetalic buried objects, and underground tunnels and cavities. It has limitations in clayey soils because of a lack of radar penetration.

8.2.3 Rapid Noninvasive Field Surveys and Screening

If a thousand soil samples are sent to the laboratory for contaminant analysis, and only one comes back as registering detectable concentration, time and money has been wasted in site characterization. There are rapid field methods for determining the extent of soil, water, and major well contamination that can help focus and direct characterization efforts and save resources. For example, surface water sampling and analysis surveys are normally simple and quick because of easy access, and are often a first measure taken at a site suspected of contamination. Certain surface waters, such as springs, gaining reaches of streams, and wetlands, often directly reflect changes in adjacent groundwater.

Unaided Methods Some survey methods are unaided, such as when soil staining is directly visible, or inferred from directly observable problems like noxious odors, stressed or dead vegetation, and impaired or dead animals. Test pits, holes for building footings, and trenches can be an easy way to observe large cross-sections of the shallow subsurface. Pits, holes, and trenches are often available at urban and industrial sites where buildings are being put in, old underground tanks are being exhumed, or underground pipelines and utilities are being established. These open holes and trenches can provide opportunities for visible identification of contamination because of large continuous exposure of the subsurface. Direct sampling of soil and any ponded water is simple with a limited risk of vertical contaminant migration. Test pits and trenches can delineate shallow stratigraphy, waste disposal areas, grossly contaminated sites, buried pipelines and underground storage tanks. Importantly, some of these site features potentially contain health hazards (e.g., toxic gases or potential trench wall collapse), and safety measures need to always be considered in these investigations.

Colorimetric Screening Techniques Classes of contaminants, like NAPLs, can be inexpensively and immediately detected by direct visual sightings in soil and water, but can be difficult when a NAPL or another pollutant of interest is clear or colorless, at low saturation, or distributed heterogeneously. NAPLs which cannot be visually detected can be quickly discovered by a number of other simple techniques. Many NAPLs like crude oil, coal tar, creosote, and other petroleum products naturally fluoresce when exposed to ultraviolet (UV) light. The inexpensive methodology of putting a soil sample in a transparent plastic bag and placing it under a "black" (UV) light is a cost effective way to screen soils for many sorts of NAPL contamination. Also for NAPLs there are hydrophobic dyes which, when put in transparent containers with soils and shaken, give indicator colors in the presence of NAPLs. In water, hydrophobic filters or hydrophobic materials can be used to detect NAPL, or centrifugation can more clearly separate a nonaqueous phase from water. A syringe needle can also be used to extract suspected globules in a surface water or groundwater sample, and the globule can be placed in a water column to observe whether it mixes, sinks, or floats. In wells, NAPL presence can be observed in a number of ways. A simple quick method is dropping and retrieving a weighted string into a well and observing whether oil phases adhere to it. The weighted string should not be reused in another well to avoid cross-contamination. Hydrocarbon detection pastes (and water detection pastes for fuel storage tanks) can additionally help differentiate oils and water.

Immunological Surveys Another rapid field screening technique for water and soils are immunological surveys where polyclonal antibodies are mixed with soils and elicit a colorimetric response in the presence of certain pollutants. Polycyclic aromatic hydrocarbons (PAHs) have been shown to be detectable with about 5% false negatives and 5% false positives in one immunological survey (Knopp et al. 2000).

■ 8.3 Minimally Invasive Soil Monitoring

Monitoring techniques which have minor perturbation of field site geologic materials include soil vapor monitoring, soil water sampling, and phytoscreening. Although some of these techniques penetrate the subsurface, the disturbance is minor and at shallow depths.

8.3.1 Soil Vapor Monitoring—Introduction

Soil-gas monitoring can be valuable for several reasons. Volatile organic liquids in the subsurface can partition into a vapor phase in the vadose zone and therefore be identified with soil gas measurement. A volatile organic liquid source may be pure oil phase product either adhering to a mineral surface or forming a nonaqueous phase layer on top of the capillary zone. It may also be dissolved in soil water or groundwater. The major benefit of soil gas screening is that it can locate zones of contamination. Identified locations of undissolved product present in the vadose zone can be recognized as a potentially persistent reservoir for ongoing contamination of groundwater, and infiltrating precipitation could dissolve the product in these zones and carry it down to the water table in the aqueous phase. Soil-gas monitoring can also be used to help determine the location of spills and leaks, and the horizontal extent of a layer of a volatile, nonaqueous phase liquid, such as gasoline, floating on the water table. Vapors from the gasoline can partition into the vadose zone, so that if they are detected by soil-gas monitoring in an area where product spills or leaks are not likely, this is an indication that the product may be migrating into the area. Additionally, soil-gas monitoring has been used as a screening method to evaluate the extent of a plume of groundwater contaminated with volatile organic compounds. The soil gas above the plume may contain volatile organics if the plume is at the water table.

Contaminant vapors themselves can be problematic. They can intrude into buildings and homes, sometimes with adverse health and safety implications (USEPA 2002). The restoration of a site may involve soil remediation if organic compounds are detected in the vadose zone. Soil vapor monitoring has been incorporated into guidelines for site investigation for some countries, for example Denmark (Algreen et al. 2015a). Under many conditions soil gas monitoring can be done much more quickly and inexpensively than installing groundwater monitoring wells. Soil gas monitoring is a noninvasive technique with little subsurface disturbance which can be used to optimize follow-on invasive methods such as well installation (ITRC 2007).

The boring is then unsealed; the vapor monitor is removed and sealed in a container for shipping to the lab, where it is analyzed (Kerfoot and Meyer 1986; NSW 2010).

Soil gas monitoring to find groundwater contamination plumes works best in areas where the vadose zone is comprised of dry, coarse-grained soils. The depth to water cannot be too deep, but at least 4.6 m (15 ft) is preferable. If the water table is too shallow, the concentration gradients are very steep, and a slight difference in depth of measurement may give a great difference in measured values (Marrin 1988). It is not possible to find an exact correlation between the soil gas concentration and contaminant concentration in the underlying groundwater. At best an order-of-magnitude correlation is possible (Thompson and Marrin 1987). Soil gas measurements are affected not only by the soil gas but also by the sampling technique and the soil-air permeability. After a rainfall, soil pores may be physically occluded by infiltrating rainwater and sampling may be impossible, particularly in finer soils. If there are several volatile organic compounds in the groundwater, they will partition into the vadose zone according to their individual Henry's law constants (Chapter 3). The organic compound with the greatest concentration in the soil gas may be the compound with the greatest Henry's law constant and not the one with the greatest concentration in the groundwater. Although care must be taken when interpreting the results of a soil gas survey, these surveys are valuable screening techniques and have significant qualitative value.

Samples of indoor air in buildings are important in identifying risks from explosive or toxic vapors, but at some sites they also show a general correlation between intrusive indoor air vapor concentrations and underlying groundwater volatile organic compound (VOC) plumes. These indoor air concentrations can vary greatly seasonally or with varying barometric pressure, but still can provide useful information which mirrors groundwater concentrations. Indoor air sampling uses a vacuum-filled ampule in which a valve is released and air is drawn in. Valve release can either be rapid for a single-time sample, or can have a slow timed release that collects an integrated sample with time.

8.3.3 Soil Water Sampling—Introduction

Contamination moving from the surface toward the water table passes through the vadose zone. Monitoring of soil-water quality in the vadose zone beneath hazardous-waste land-treatment systems is required under Subtitle C of the Resource Conservation and Recovery Act in the United States. States may also require vadose-zone monitoring beneath other types of hazardous-waste facilities.

In order to determine the chemical composition and quality of soil moisture in the vadose zone, a sample must be collected. Because the soil water in the vadose zone is under tension, it cannot flow into a well under gravity the way that groundwater flows into a well. Soil water must be collected with a suction lysimeter (Wilson 1990).

8.3.4 Suction Lysimeters

A **suction lysimeter** is a porous cup located on the end of a hollow tube. The tube can be PVC or even stainless steel. The porous cup can be ceramic, nylon, PFTE, or fritted stainless steel. Tubing connects the suction lysimeter with the surface.

A suction is applied to the hollow tube and held for a period of time. If the suction is greater (more negative) than the soil-moisture tension in the soil, a potential gradient will develop from the soil to the porous cup. Soil-water will flow into the porous cup, from which it can then be directed through the tubing to the surface for collection. The flow of soil moisture can be slow, and it may be necessary to hold the vacuum overnight to supply a sufficient volume.

A vacuum lysimeter simply has a porous tip on the end of a hollow tube with a stopper that extends to the surface. The vacuum is applied to the lysimeter by means of a hand-vacuum pump attached to a small tube that extends down to the porous tip, and a sample is drawn to the surface when vacuum is applied (Figure 8.1). The practical depth of this type of sampler is about 1.8 m (6 ft) due to the awkwardness and cost of installing long tubes (Wilson 1990).

A pressure-vacuum lysimeter has a hollow tube that is about 5.08 cm (2 in.) in diameter and 0.3 m (1 ft) long. Two tubes run from the lysimeter to the surface (Figure 8.2). One of the tubes, the discharge line, extends to the bottom of the lysimeter and the other tube, the pressure-vacuum line, ends near the top. A vacuum is applied to the pressure vacuum line with a vacuum pump while the discharge line is shut off with a pinch clamp. The pressure-vacuum line is then sealed with a pinch clamp and the lysimeter is allowed to sit overnight so that the sample can be drawn into the cup. The pinch clamps are then removed. A hand-pressure pump is then attached to the pressure-vacuum line, and when pressure is applied, the water is forced up the discharge line to the surface. (A single pressure-vacuum hand pump can be used for this operation.) The maximum practical operational depth for the pressure vacuum pump is about 15 m (50 ft). At depths

FIGURE 8.1 Operation of a vacuum lysimeter.

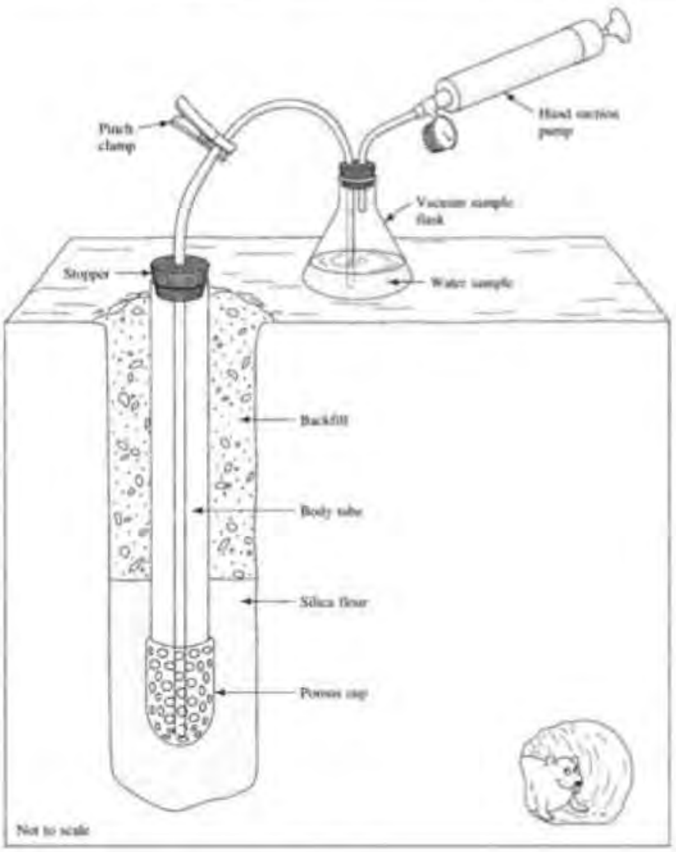
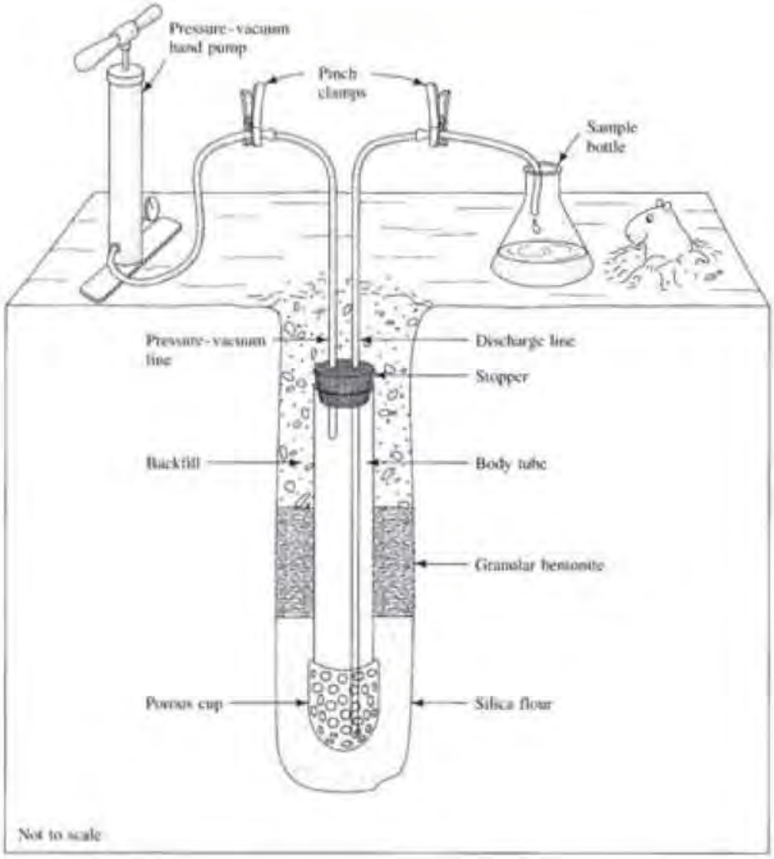


FIGURE 8.2 Operation of a pressure-vacuum lysimeter.



greater than this, the pressure needed to force the sample to the surface tends to drive it back out of the porous cup. This can be avoided by using a lysimeter with a check valve and an internal reservoir (Figure 8.3). When the vacuum is applied the water is drawn into the reservoir. When the pressure is then applied, the check valve prevents backflow into the porous cup and the sample must go to the surface.

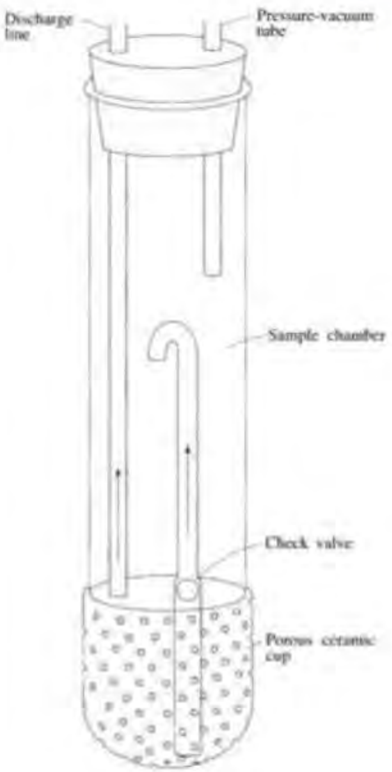
8.3.5 Installation of Suction Lysimeters

In order for suction lysimeters to work properly, they must be carefully installed (Wilson 1991). Prior to use, new porous ceramic cups should be leached with a 10% hydrochloric acid solution for 24 hours to remove dust from manufacturing. They should then be thoroughly rinsed by passing distilled water through them. The lysimeter is then pressure tested before being installed by submerging it in water and applying a pressure of 207 kpa (30 lb/in.^{2}) to test for leaks. No leaks should appear at any fittings, and air should bubble evenly through the porous cup.

The suction lysimeter is installed in an augered hole that has a greater diameter than the hollow tube. If the suction lysimeter is placed at a shallow depth, less than about 3 m (10 ft), then the access hole can typically be made by a hand auger. If it is greater than that depth, then a hollow-stem auger-drilling rig is needed to auger a hole.

The porous tip must be well bedded in slurry made of 200-mesh silica flour or native soil material that has been dried and screened to remove the fraction larger

FIGURE 8.3 Design of a pressure-vacuum lysimeter with a sample chamber and a check valve.



than coarse sand. There needs to be good hydraulic contact with the porous cup, the bedding material, and the native soil. Prior to installation the porous tip should be well hydrated by soaking in distilled water.

If a hollow-stem auger is being used, the augers should first be pulled back about 0.61 m (2 ft) to expose the native soil. A slurry made from silica flour and distilled water (0.45 kg (1 lb) of 200-mesh silica flour and 150 mL of distilled water) is put into the hole with a tremmie pipe to fill the hole with about 15.25 cm (6 in.) of slurry. The suction lysimeter is then lowered into the hole and centered. The tremmie pipe is then used carefully to place the slurry around the lysimeter up to an elevation of about 0.3 m (1 ft) above the top of the lysimeter. The unit should be held in place until the water drains from the slurry. The unit is then tested to see if it will hold a vacuum of 60 Kpa (0.6 bars). If it does, the augers are pulled back another 0.91 m (3 ft); then about 0.3 m (1 ft) of sieved native soil and 0.61 m (2 ft) of bentonite granules are added. The tremmie pipe is used to add distilled water to the bentonite to hydrate it. Finally, the augers are pulled and the borehole is backfilled with native soils that are tamped down to ensure compaction. Since a lot of distilled water was added to the soil during installation, the lysimeter needs to be purged until consistent water quality is obtained.

8.3.6 Phyto-screening

Phyto-screening is based on the ability of plants to translocate contaminants from their root zone to plant tissues above ground. Because the root zones of plants can be relatively large and their capture areas in the soil ill-defined, the method is somewhat qualitative, but potentially useful, particularly in locales with shallow groundwater contamination at large sites. Trees can draw water from groundwater, the capillary fringe, and/or pore water in the vadose zone, and therefore phyto-screening can supplement and enhance soil gas screening techniques (Algreen et al. 2015a). Often tree coring or plant tissue harvesting is used as a collection and detection method for determining the location of subsurface pollutants. Coring and use of plant tissues has been used, with certain limitations, to locate chlorinated solvents (Vroblesky, Nietch, and Morris 1999; Orchard et al. 2000; Vroblesky et al. 2004; Sorek et al. 2008; Larsen et al. 2008; Limmer et al. 2011), BTEX compounds (Algreen et al. 2015b; Wilson et al. 2013) and heavy metals (Stefanov et al. 2012; Algreen et al. 2012; 2014).

8.4 Invasive Methods - Monitoring Well Design

8.4.1 General Information

Monitoring wells are installed for a number of different purposes. During the installation of a monitoring well, a soil boring may be made or rock-core samples may be collected to determine the basic geology of the site. Prior to the design of a well, it is necessary to determine what its use will be. Some purposes of monitoring wells include:

- Measuring the elevation of the water table.
- Measuring a potentiometric water level within an aquifer, or at several depths in an aquifer.
- Collecting water samples for chemical analysis.
- Collecting samples of a nonaqueous phase liquid that are less dense than water.
- Collecting samples of a nonaqueous phase liquid that are more dense than water.
- Testing the permeability of an aquifer or aquiclude at discrete depths.
- Providing access for geophysical instruments.
- Collecting a sample of soil gas.

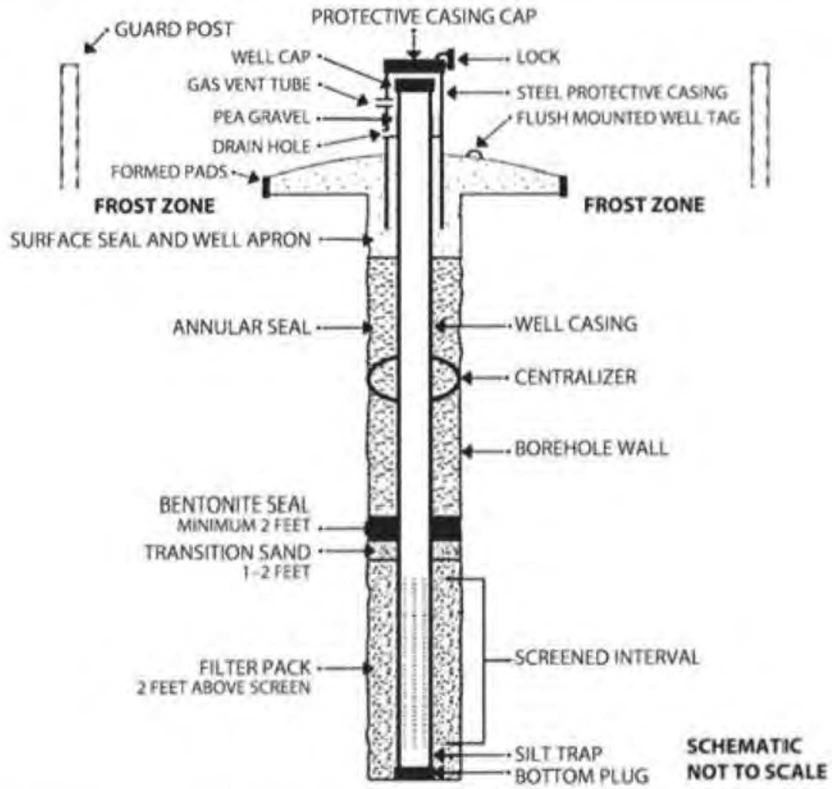
The use for which the well is intended will dictate the design. For example, if a well is to be used for the collection of water samples, the casing must be large enough to accommodate the water-sampling device. However, the diameter should not be much larger than the minimum size, because prior to the sampling of a well, stagnant water must be removed from the casing; the larger the diameter of the casing, the greater the volume of water that must be pumped and properly disposed. Some slightly more expensive characterization techniques can be well worth it for understanding a site. For example, high-resolution multilevel wells can produce orders of magnitude more data and understanding than single-screened wells. Figure 8.4 is a generalized schematic of a typical monitoring well. The following factors should be specified in the design of a monitoring well:

- Type of casing material.
- Diameter of the casing.
- If there will be a well screen, multiple screens, or an open borehole.
- If there is an open borehole, how deep the surface casing should be set. Cross connections between separate aquifers should be avoided.
- Length of casing.
- Depth of the well.
- Number of target sampling depths and screened intervals necessary in each well.
- Setting and length of the well screen(s).

- Diameter of well screen(s).
- Type of material for well screen(s).
- Slot opening of well screen.
- If an artificial filter pack (gravel pack) is necessary.
- Gradation of filter pack (gravel pack) material.
- Method of installation of well and screen.
- Material used to seal annular space between casing and borehole wall.
- Protective casing or well vault.

Monitoring network design is determined not only by intended well uses, but physical factors in the locale. Site specific influences of geography, practical consideration of surface conditions, and subsurface variability determine network monitoring design (Arnold et al. 2009). Geographical factors include natural and human-made topographic anomalies; natural and engineered surface drainage routes; areas of potential recharge and discharge such as wetlands; factors which influence the overall water balance such as weather and climatic variability; and anthropogenic features such as buildings, pavement, and pipelines. The practicalities of site accessibility and compatibility of monitoring wells with facility operations is often an important factor in well placement. Subsurface conditions also help dictate well network design. In general, more monitoring wells with closer intervals between wells, and multilevel sampling ability are required if there is complicated geology (e.g., discontinuous structures, tight folds, closely spaced

Figure 8.4 Typical monitoring well.



Source: E. Hughes and G. Aarons. 2014. *Well Design and Construction for Monitoring Groundwater at Contaminated Sites*. The California Environmental Protection Agency.

fractures, faults, solution channels), heterogeneous conditions (e.g., variable hydraulic conductivity, variable lithology), steep or variable hydraulic gradients, low dispersivity potential, high flow velocities, or if the aquifer is located near a recharge zone. Depths to water tables, confining layers, and bedrock surfaces are key in decisions about screen intervals and drilling depths. Lastly, the number and placement of wells often is based on prior application of noninvasive methods. These can include indirect methods (such as surface geophysics, soil gas where applicable, airborne remote sensing) or direct observation (such as existing wells, soil borings, test pits, and observation of local outcrops).

Common problems with groundwater monitoring systems include instances where wells are placed by regulatory mandate; where there is incomplete site data; when initial ideas on site (and regional) geology, hydrogeology, and water balance are not correct; and when incorrect assumptions are made regarding waste constituent migration. Difficulties also arise with improperly constructed wells, when they are not properly identified, or in cases when wells are not properly surveyed for location and elevation.

8.4.2 Monitoring Well Casing

All monitoring wells have a **casing**, whether they have a screen or terminate in an open borehole in bedrock. The casing is a piece of solid pipe that leads from the ground surface to the well screen or open borehole and is intended to keep both soil and water from entering the well other than through the screen or open borehole. Casing also prevents water from flowing from one aquifer horizon to another, provided the annular space outside the casing is properly sealed.

The diameter of the casing for a monitoring well is determined by the use for which the monitoring well is planned. If the only purpose of the monitoring well is to measure water levels, then a 2.54 cm (1 in.) inside-diameter casing is all that is needed. An electric probe to measure water level or a pressure transducer will fit inside the 2.54 cm (1 in.) casing. Figure 8.5 shows an electric probe being lowered into a 5.08 cm (2 in.) casing.

If a well is to be used to collect a groundwater sample, the diameter of the well needs to be such that standard well-sampling equipment can fit inside. The common standard for well-sampling equipment is a nominal 5.08 cm (2 in.) diameter. This can accommodate a wide variety of pumps that can withdraw water at rates of 0.03 to 0.13 or 0.19 L/s (0.5 to 2 or 3 gal./min). Specially designed borehole geophysical equipment can also fit inside a 5.08 cm diameter casing.

For some applications, monitoring wells may be intended for several functions such as measuring water levels, collecting water samples, pumping to remove contaminated water and perhaps floating nonaqueous phase liquids, and as a part of a vapor-extraction system. These wells sometimes have diameters larger than 5.08 cm (2 in.) to accommodate pumping equipment with a higher-flow capacity. The actual equipment to be used determines the casing diameter.

Casing diameter can also be influenced by the depth of the well. The deeper the well, the stronger the casing and screen must be to resist the lateral pressure at the final depth and the crushing force of the weight of the length of casing. Larger diameter casing can be made with thicker walls to have greater strength. It is easier to have a straight well with stronger casing. Straight wells are important in accommodating bailers and pumps.

The outside diameter of casing is standard; however, the inside diameter is a function of the wall thickness. Table 8.1 lists the wall thickness and inside diameter for

FIGURE 8.5 Electric probe used to measure water levels in monitoring wells.

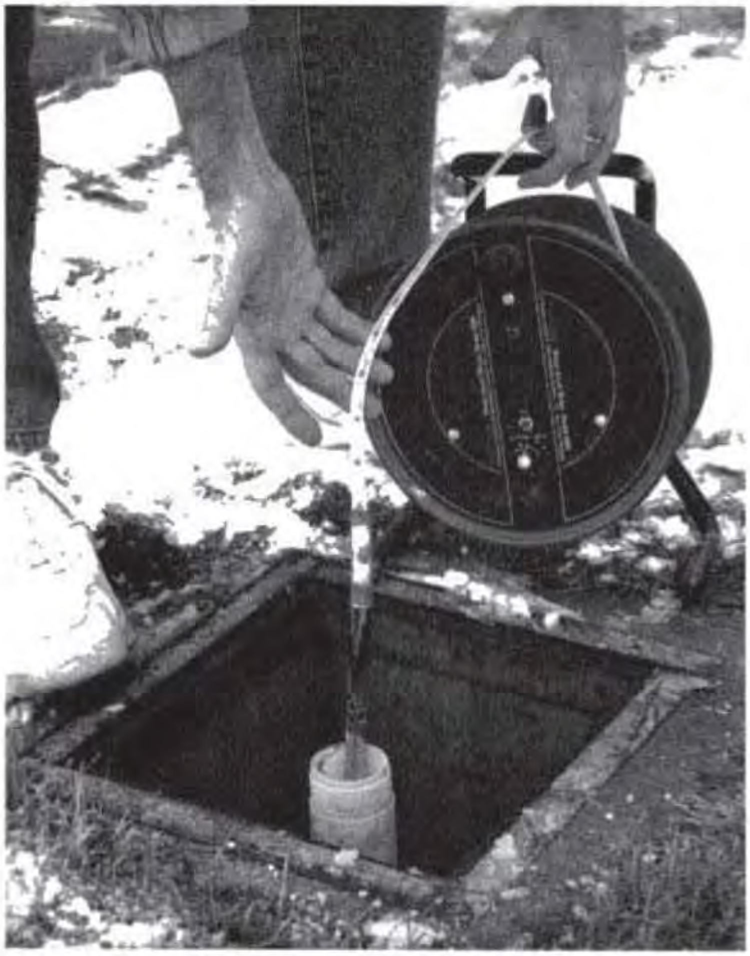


Photo credit: Jim Labre.

TABLE 8.1 Dimensions of inside and outside diameters of well casings.

		Schedule 5		Schedule 10		Schedule 40		Schedule 80	
Pipe Size	Outside Diameter	Wall Thickness	Inside Diameter	Wall Thickness	Inside Diameter	Wall Thickness	Inside Diameter	Wall Thickness	Inside Diameter
Nominal 2"	2.375"	0.065"	2.245"	0.109"	2.157"	0.154"	2.067"	0.218"	1.939"
Nominal 3"	3.500"	0.083"	3.334"	0.120"	3.260"	0.216"	3.068"	0.300"	2.900"
Nominal 4"	4.500"	0.083"	4.334"	0.120"	4.260"	0.237"	4.026"	0.337"	3.826"
Nominal 5"	5.563"	0.109"	5.345"	0.134"	5.295"	0.258"	5.047"	0.375"	4.813"
Nominal 6"	6.625"	0.109"	6.407"	0.134"	6.357"	0.280"	6.065"	0.432"	5.761"

various schedules of casing. The sizes are listed in English units (inches) as many casings and screens were produced for decades in countries not yet on the metric system. Table 8.2 lists recommendations for selection of casing and screen material. Heavier-schedule casing is stronger because it has a thicker wall. The strength of a casing also depends upon the material from which it is constructed. A schedule 5 casing

TABLE 8.2 Recommendations for selection of casing and screen material.

	Do Not Use:	Use:
1	PTFE if well depth exceeds 225–375 feet (68.6–14 meters)	PVC, ABS, SS
2	PVC or ABS if well depth exceeds 1200–2000 feet (366–610 meters)	SS
3	SS if pH < 7.0	PVC, ABS or PTFE
4	SS if D.O. > 2 ppm	PVC, ABS or PTFE
5	SS if H_2S > 1 ppm	PVC, ABS or PTFE
6	SS if TDS > 1000 ppm	PVC, ABS or PTFE
7	SS if CO_2 > 50 ppm	PVC, ABS or PTFE
8	SS if Cl^- > 500 ppm	PVC, ABS or PTFE
9	PVC if a neat PVC solvent/softening agent* is present or if the aqueous concentration of the PVC solvent/softening agent exceeds 0.25 times its solubility in water	SS, PTFE
10	Solvent-bonded joints for PVC casings	Threaded PVC casings
11	Welding stainless joints	Threaded SS casings
12	Any PVC well casing that is not NSF-ASTM approved—D-1785 and F-480	NSF-ASTM approved PVC well casings—D-1785 and F-480
13	Any stainless steel casing that is not ASTM approved—A312	ASTM approved SS 304 and SS 316 casings—A312
14	Any ABS well casing that is not ASTM approved	ASTM approved ABS casings—F-480

*Known PVC solvents/softening agents include:
Tetrohydrofuran, cyclohexane, methyl ethyl ketone, methyl isobutyl ketone, methylene chloride, trichloromethane, 1,1-dichloroethane, 1,1,1-trichloroethane, trichloroethylene, benzene, toluene, acetone, and tetrachloroethylene.

ABS	Acrylonitrile butadiene styrene
D.O.	Dissolved oxygen
ppm	parts per million
PTFE	Polytetrafluoroethylene
PVC	Polyvinyl chloride
SS	Stainless steel
TDS	Total dissolved solids

Source: E. Hughes and G. Aarons. 2014. *Well Design and Construction for Monitoring Groundwater at Contaminated Sites*. The California Environmental Protection Agency.)

made of stainless steel is stronger than a schedule 40 casing made of polyvinyl chloride (PVC), yet leaves a greater inside diameter.

There are a number of materials used to make well casings and screens. These materials vary in chemical inertness, strength, durability, ease of handling, and cost. One must always consider the intended use of the monitoring well before selecting a material. What is the chemistry of the groundwater and associated contaminants?

Will any compounds present in the groundwater react with any of the possible casing materials? How deep will the well be? What are the strength requirements? Is the well intended for a short-term monitoring project or will it remain in service for many years?

Well casings are available in a variety of materials: fluoropolymers, such as PTFE, or polytetrafluoroethylene (Teflon® is the brand name of one manufacturer of PTFE), mild steel, galvanized steel, stainless steel, polyvinyl chloride (PVC), acrylonitrile butadiene styrene (ABS), fluorinated ethylene propylene (FEP), fiberglass-reinforced epoxy (FRE), polypropylene, and fiberglass-reinforced plastic (FRP). The ideal casing material is inexpensive, strong, not subjected to degradation in the environment, and will not affect water-quality samples by either leaching chemicals into or sorbing them from the groundwater (Ranney and Parker 1997). Mild or galvanized steel is often used for water-supply well casings but is not as frequently found in monitoring wells because it may react with the groundwater to leach metals from the casing (Barcelona et al. 1983). Polypropylene, FEP, and ABS are not widely available. Most monitoring wells are made of stainless steel or PVC, with PTFE being less common. PVC casing is the least expensive. Relative casing costs for other materials, compared with PVC, are mild steel = 1.1, polypropylene = 2.1, type 304 stainless steel = 6.9, type 316 stainless steel = 11.2, and PTFE = 20.7. Type 316 stainless steel is more resistant to corrosion than type 304 under reducing conditions (Aller et al. 1991).

Stainless steel has the greatest strength, followed by mild steel. Both are also resistant to heat, but they are heavier than the plastics and are, therefore, more difficult to install. The lower strength of the plastics is compensated for by using a heavier-schedule casing than necessary with steel. Most monitoring wells are shallow enough that schedule 40 or 80 PVC has sufficient strength. PTFE is more brittle and has less wear resistance than PVC or polypropylene and is hence less durable. PTFE also has a low tensile strength and high weight per unit length, which limits its use to shallow depths. Even there, PTFE casing tends to bow under its weight when installed in monitoring wells and may not be straight and plumb. Although its nonstick properties are good in frying pans, the neat cement grout used to seal the annular space between the casing and the borehole may not bond to the PTFE casing (Nielsen 1988). Table 8.3 gives comparative strengths of casing materials.

Groundwater monitoring wells can come into contact with pure organic compounds (LNAPLs and DNAPLs) as well as highly acidic and highly basic conditions. Ranney and Parker (1997) tested six different materials that are used or could be used as monitoring well casings in order to test their resistance to pure (neat) organic chemicals and acids and bases. (Stainless steel and galvanized steel are known to be unaffected by organic compounds but susceptible to corrosion by acids and bases.) They found that PTFE and FEP were unaffected by any of the 28 different organic chemicals in which they were immersed. The other four materials—PVC, ABS, FRE, and FRP—were affected to some degree by some, or in the case of ABS, all of the 28 chemicals. This study suggests that if contact with neat organic compounds is possible, PTFE, FEP, or stainless steel casings should be considered, although some PTFE materials are slightly porous, and are deformable and "ductile" under loading.

In the selection of casing material for groundwater monitoring wells, we must consider the potential chemical reactions between the casing material and the groundwater. Ideally, casing material should neither leach matter into water nor sorb

TABLE 8.3 Comparative strengths of casing materials. Note: 1 lb = 0.454 kg and 1 lb/in^2 = 0.07 kg/cm^2.

Material	Casing Tensile Strength (lb)		Casing Collapse Strength (lb/in^2)	
	2-inch diameter nominal	4-inch diameter nominal	2-inch diameter nominal	4-inch diameter nominal
Polyvinyl chloride (PVC)	7,500	22,000	307	158
PVC casing joint[b]	2,800	6,050	300	150
Stainless steel (SS)[c]	37,760	92,000	896	315
SS casing joint[b]	15,900	81,750	No data	No data
Polytetrafluoroethylene (PTFE)	3,800	No data	No data	No data
PTFE casing joints[b]	540	1,890	No data	No data
Epoxy fiberglass	22,600	56,500	330	250
Epoxy casing joints[d]	14,000	30,000	230	150
Acrylonitrile butadiene styrene (ABS)	8,830	22,000	No data	No data
ABS casing joints[d]	3,360	5,600	No data	No data

a Information provided by E. I. du Pont de Nemours & Company, Wilmington, DE.

b All joints are flush-threaded.

c Stainless steel casing materials are Schedule 5 with Schedule 40 joints; other casing materials (PVC, PTFE, epoxy, ABS) are Schedule 40.

d Joints are not flush-threaded, but are a special type that is thicker than Schedule 40.

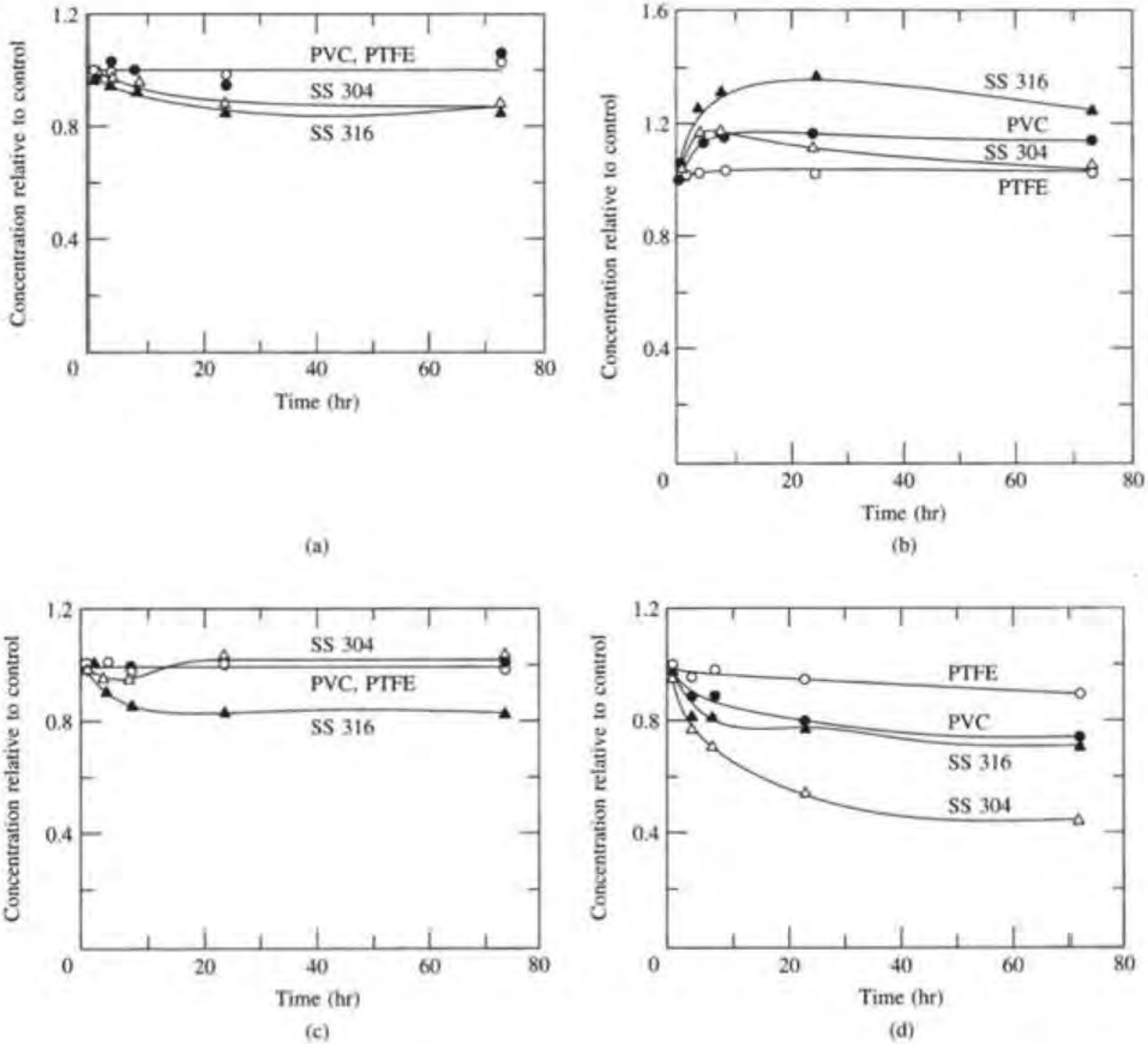
Source: E. Hughes and G. Aarons. 2014. *Well Design and Construction for Monitoring Groundwater at Contaminated Sites*. The California Environmental Protection Agency.)

chemicals from water. Table 8.4 shows general recommendations for casing/ screen material selection.

Reynolds and Gillham (1985) studied the sorption from aqueous solution of five halogenated organic compounds by several polymer materials. The organic compounds used were 1,1,1-trichloroethane, 1,1,2,2-tetrachloroethane, hexachloroethane, perchloroethene, and bromoform. The materials tested were PVC, PTFE, nylon, polypropylene, polyethylene, and latex rubber. Nylon, polypropylene, polyethylene, and latex rubber rapidly absorbed all five compounds. PVC absorbed all the compounds but 1,1,1-trichloroethane, although the rate of absorption was low. PTFE absorbed all the compounds but bromoform; although the rate of adsorption of three of the four remaining compounds was low, PTFE absorbed 50% of the perchloroethylene in 8 hours.

Parker, Hewitt, and Jenkins (1990) evaluated the suitability of PVC, PTFE, stainless steel type 304 (SS 304), and stainless steel type 316 (SS 316) as casing material for monitoring metals in groundwater. They evaluated the interaction of four trace elements that are of concern in groundwater studies: arsenic, cadmium, chromium, and lead. The metals were tested at concentrations of 50 and 100 μg/L dissolved in groundwater. Figure 8.6 shows the results of this study. If the concentration relative to

FIGURE 8.6 Sorption and leaching of a. arsenic, b. cadmium, c. chromium, and d. lead by well casings made from PVC, PTFE, type 304 stainless steel, and type 316 stainless steel.

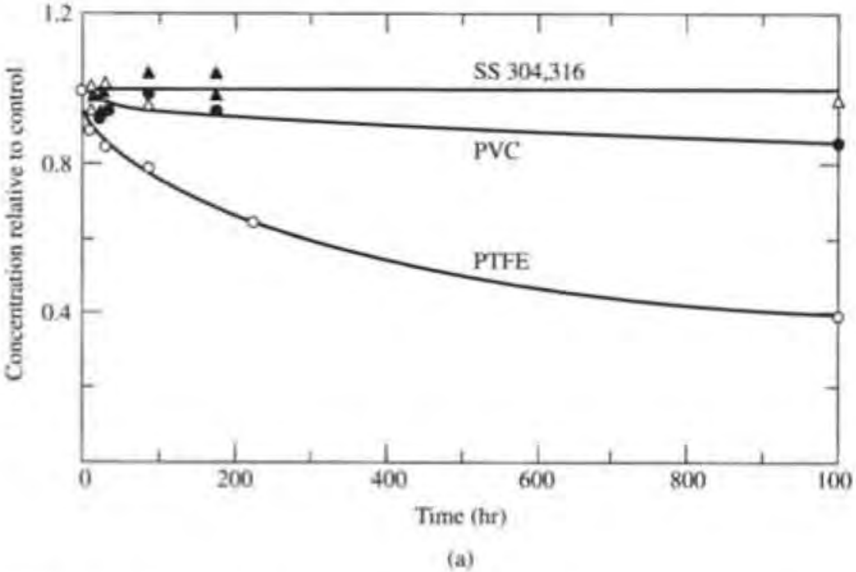


Source: L. V. Parker, A. D. Hewitt, and T. F. Jenkins. 1990. Influence of casing materials on trace-level chemicals in ground water. *Groundwater Monitoring & Remediation* 10:146–156. Used with permission.

for well casing should be used, and in the United States it should carry the designation *NSF wc*, which indicates that the casing conforms to National Sanitation Foundation Standard 14 for potable water supply (National Sanitation Foundation 1988).

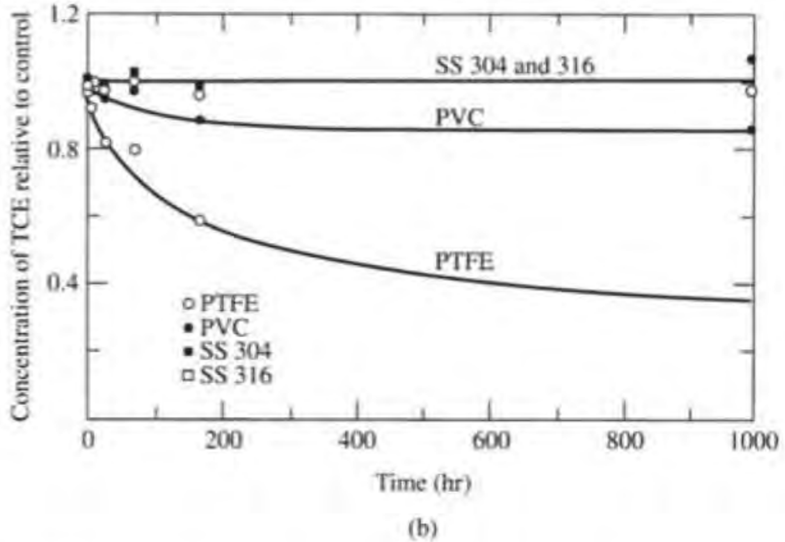
However, PVC should be avoided if organic compounds are present in the ground as nonaqueous phase liquids. Likewise, PVC casing should also never be joined with solvent-glued joints. These solvents include compounds such as methylethylketone and tetrahydrofuran and they may leach into groundwater samples. Threaded joints that are machined directly onto the PVC are the preferred method of joining casing sections and casing to screen. Joints should be flush on the inside of the casing to prevent equipment being lowered into the casing from hanging up in a projecting joint inside

FIGURE 8.7a Sorption of trichloroethylene in the part per million range from groundwater by PVC, PTFE, type 304, and type 316 stainless steel well casings.



Source: L. V. Parker, A. D. Hewitt, and T. F. Jenkins. 1990. Influence of casing materials on trace-level chemicals in ground water. *Groundwater Monitoring & Remediation* 10:146–156. Used with permission.

FIGURE 8.7b Sorption of trichloroethylene in the part per billion range from by PVC, PTFE, type 304, and type 316 stainless steel well casings.



Source: L. V. Parker and T. A. Ranney. 1994. Effect of concentration on sorption of dissolved organics by PVC, PTFE and stainless steel well casings. *Groundwater Monitoring & Remediation* 14:139–149. Used with permission.

the well, or bridging and stoppage of grout or filter pack material in the annular space outside the well.

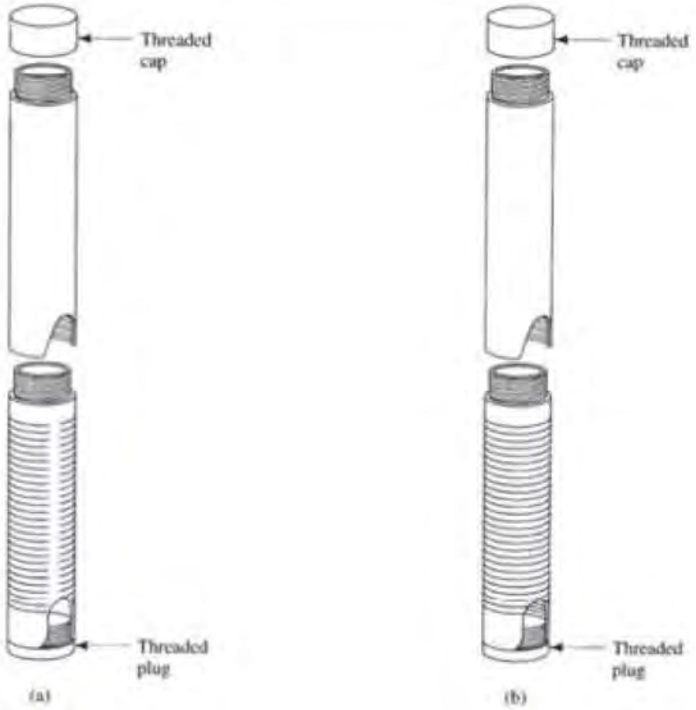
There are groundwater contaminants other than either metals or dissolved nonpolar organic compounds. Many chemicals associated with agriculture are strongly polar or ionic. Papiernik, Widmer and Spalding (1996) studied the impact of using various materials to sample agricultural contaminants, including nitrate-N, atrazine, diethylatrazine, diisopropylatrazine, cyanazine, alachlor, metolachlor and butachlor. They found that other than butachlor (which is not in common use in the United States) there was no significant difference in absorption of the target by either polytetrafluoroethylene (PTFE), rigid PVC, flexible PVC, stainless steel, high density polyethylene (HDPE), or low density polyethylene (LDPE). For any of the chemicals tested, other than butachlor, any of the materials could be used. The least expensive would be HDPE, LDPE, and rigid PVC.

8.4.3 Monitoring Well Screens

If the monitoring well terminates in an unconsolidated formation, a **screen** is necessary to allow the water to enter while keeping the sediment out. In most monitoring well applications, the well screen is the same diameter as the casing to which it is attached by a threaded coupling. Likewise, the well screen is normally made of the same material as the casing. The considerations that go into deciding the material to use for the casing also apply to the screen. In many cases multilevel sampling will provide crucial information and multiple, isolated screened intervals are necessary.

The screen or screens will have openings to permit the water to enter. Manufactured well screen should always be used rather than hand-cut slots or drilled holes in plastic pipe. The two common screens for monitoring wells are slotted pipe, which is available in PVC and PTFE, and continuous wire wrap, which is available in stainless steel. Figure 8.8 illustrates these two screen types.

FIGURE 8.8 Slotted (a) and continuous wire-wrapped (b) monitoring well screens.



The width of the slot or wire-wrap opening is precisely controlled during the manufacture of the screen; the screen is available in a variety of opening sizes, generally ranging from 0.02 to 0635 cm (0.008 to 0.250 in.) A screen with an opening of 0.010 in. (0.0254 cm) is referred to as a 10-slot screen. Many manufacturers carry only a limited number of slot sizes in stock—for example, 10- and 20-slot. Since the casing and screen are typically ordered in advance of the well construction, the hydrogeologist usually has settled on a standard design prior to going on the job. Decisions on slot sizes are important in that too large a slot size without proper filter pack can allow sediment to enter the well during pumping. Conversely, a small slot size can inhibit nonaqueous phase liquids (NAPLs) from entering a well. NAPL must have enough thickness and fluid pressure to supplant water in small slots, overcoming capillary pressure. If well screen slots have small opening sizes, NAPL outside the well in a thin pool may not be able to enter through the screens.

8.4.4 Naturally Developed and Filter-Packed Wells

The casing and screen may be placed in the borehole and the native sediment allowed to cave around the screen. This is called a **naturally developed well** and is often used in sandy sediment with very limited amounts of silt and clay present, but is most realistic for wells with single screens. At least 90% of the sediment should be retained on a 10-slot screen before a naturally developed well is considered (Aller et al. 1991). When water is withdrawn from such a well, it may initially be cloudy due to suspended silt and clay, but the water should eventually clear as the fines near the screen are removed by a process called "well development." In a naturally developed well the slot size is selected to allow some of the fine sediment to enter the well during development; this leaves only the coarser sediment outside the screen.

In designing a water well, it is very important that the well be hydraulically effective—i.e., there should be a minimal loss of energy as the water flows into the well. As mentioned, the selection of the slot opening for naturally developed water wells is very important and is based on a grain-size distribution curve of the sediment opposite the well screen. Monitoring wells are designed to retain much more of the natural formation than water wells because they are much more difficult to develop (Driscoll 1986). Monitoring wells are not usually designed with the precision necessary for a water-supply well. The well should be hydraulically efficient as well as being as clear of silt and clay as possible. If preliminary investigations indicate that the aquifer to be monitored has reasonably coarse sand or gravel and few fines, a standard slot size may be preselected for all the monitoring wells. Ten-slot screen is frequently used under these conditions.

If the formation is cohesive—that is, has a high clay content—or if it is sandy with a high silt content, it will be necessary to use an **artificial filter pack**. Filter packs have also been referred to as "sand packs" or "gravel packs." Filter-pack material is typically medium to coarse sand that is predominately silica with no carbonates. It is mined and graded to have a specific grain-size distribution. Manufactured filter-pack material comes washed and bagged and is far preferable to native sand as artificial filter pack. The filter-pack material is placed in the borehole opposite the well screen. Its purpose is to stabilize the natural formation and keep it out of the screen. This will reduce the amount of silt and clay that enters the well when it is developed. There are also dual-screen well intake systems (pre-packs) that have a small diameter screen within a larger, second larger diameter screen, and the space in between is filled with filter pack material. Dual screen intakes are sometimes used when there is a propensity for fine-grained material to enter the well. A major disadvantage of these systems is that the two screens can compound the inhibition of NAPLs to enter a well.

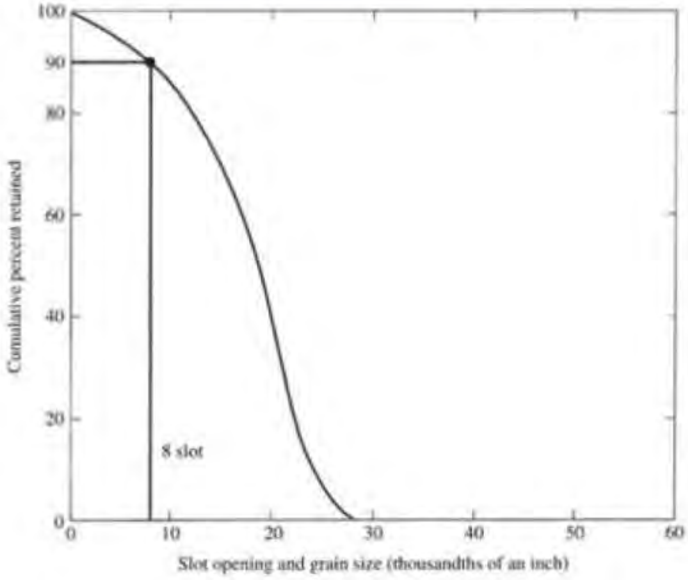
The grain size of the filter-pack material is based on the nature of the formation opposite the screen. If the formation is fine sand, then the grain-size distribution is determined. The filter pack material should have an average grain size that is twice the average grain size of the formation and have a uniformity coefficient (ratio of 40% retained size to 90% retained size) between 2 and 3 (Driscoll 1986). The screen-slot opening is then selected to retain 90% of the filter pack. The minimum practical slot size for monitoring well screens is 0.02 cm (0.008 in.) Figure 8.9 shows a grain-size distribution curve for a filter-pack material designed for an eight-slot screen. If the monitoring well is in silt or clay, all one can do is install an 8 slot screen and appropriate filter pack.

The filter-pack material should be approximately 5 to 7.5 cm (2 to 3 in.) thick. This means that a 5 cm (2 in.) diameter well screen should be installed in a borehole about 10 to 15 cm (6 to 8 in.) in diameter. The filter-pack material is normally extended 0.61 or 0.91 m (2 or 3 ft) above the top of the well screen to allow for settlement of the material during development.

8.4.5 Annular Seal

The **annular space** in the borehole above the filter pack must be sealed to prevent the movement of surface water downward to the filter pack. It may also be sealed to prevent vertical movement of groundwater from one zone to another or to isolate a discrete sampling zone. The seal should be made of a material that has a low permeability, bonds well to the natural formation and the casing, and expands after it has been

FIGURE 8.9 Grain-size distribution curve used to select an eight-slot screen for a monitoring well.



emplaced to ensure a tight seal. It should set up within a day or so and be durable and permanent.

Materials typically used for an annular seal are bentonite pellets, granular bentonite slurry, neat cement grout, bentonite-sand slurry, and neat cement grout with a powdered bentonite additive.

Neat cement grout is a mixture of 42.5 kg (94 lb) of type I Portland cement with about 19 to 23 L (5 to 6 gal.) of water. Granular bentonite slurry is a mixture of 13.6 kg (30 lb) of untreated bentonite powder mixed with 56.7 kg (125) lb of untreated bentonite granules with 378.5 L (100 gal) of water. Bentonite-cement grout is a mixture of 2.3 kg (5 lb) of untreated powdered bentonite with 42.5 kg (94 lb) of type I Portland cement and 32 L (8.5 gal.) of water. Bentonite-sand slurry is a mixture of 25 kg (55 lb) of untreated powdered bentonite with 378.5 L (100 gal.) of water and 10 to 25% sand by volume to make a slurry that weighs 9.6 kg/L (11 lb/gal.) All water used to make these slurries should be from a source that is fresh and known to be uncontaminated and free from floating oil.

Bentonite is a clay containing at least 85% sodium montmorillonite; it will swell to several times its original volume when thoroughly hydrated. This hydration takes place below the water table. However, bentonite has a high cation-exchange capacity and can affect the chemistry of water that comes into contact with it. Portland cement is used to make cement grout. When Portland cement cures, it is highly alkaline and can affect the pH of groundwater that comes into contact with it. Neat cement grout will shrink by at least 17% when it cures. The addition of bentonite to make a bentonite-cement grout significantly reduces the shrinkage problem. If neat cement grout or bentonite cement grout is used, the casing material should be either stainless steel or schedule 80 PVC due to the heat generated as the cement cures.

The materials available for an annular seal are not ideal. Although they can be used to make an impermeable seal, there is a chance they might affect groundwater quality in their immediate vicinity. This problem is mitigated if 0.61 m (2 ft) of fine sand is placed in the annular space above the filter-pack material or native sand opposite the screen. This keeps the annular seal material from coming into contact with the water entering the well screen.

Many hydrogeologists place a 0.61 m or 0.91 m (2 or 3 ft) layer of bentonite pellets above the fine sand if the pellets will be below the water table. The pellets will swell and keep the grout material from entering the filter-pack material. Clay pellets should not be used in the vadose zone due to lack of hydration and lack of swelling; a clay slurry should be used instead. If the top of the 0.61 m (2 ft) fine-sand seal is above the water table, then 0.61 m (2 ft) of granular bentonite may be placed prior to the addition of the annular seal.

8.4.6 Protective Casing

In order to provide physical protection for the investment in a costly monitoring well, as well as to protect from vandalism by individuals accidentally or intentionally putting foreign fluids and objects into a monitoring well, a locking protective steel casing or well vault is needed.

A protective casing extends several feet above the ground surface. It extends above the top of the monitoring well and has an inside diameter sufficiently large so that the hydrogeologist can reach inside and unscrew a cap from the monitoring well. It is set into a surface cement seal. For monitoring wells installed in freezing climates, a drain hole at the bottom of the surface casing is desirable to prevent accumulation of moisture that could freeze in the annular space between the protective casing and the monitoring well. (One of the authors has seen a stainless-steel monitoring well casing pinched shut by water that accumulated in a protective casing without a drain hole and then froze!)

In some applications, it is not practical to have a monitoring well that extends above ground—for example, in the driveway at a gas station. There are small well vaults available that can be used for protection for monitoring wells. However, they should be in places that are not going to flood; otherwise floodwaters could enter the aquifer via the monitoring well. If a well vault is used in a gas station or similar location, it should be clearly marked and should be distinctive from the fillers for underground storage tanks so that an inattentive person does not try to fill it with gasoline! A locking well cap without a vent hole should also be used.

8.4.7 Screen Length and Setting

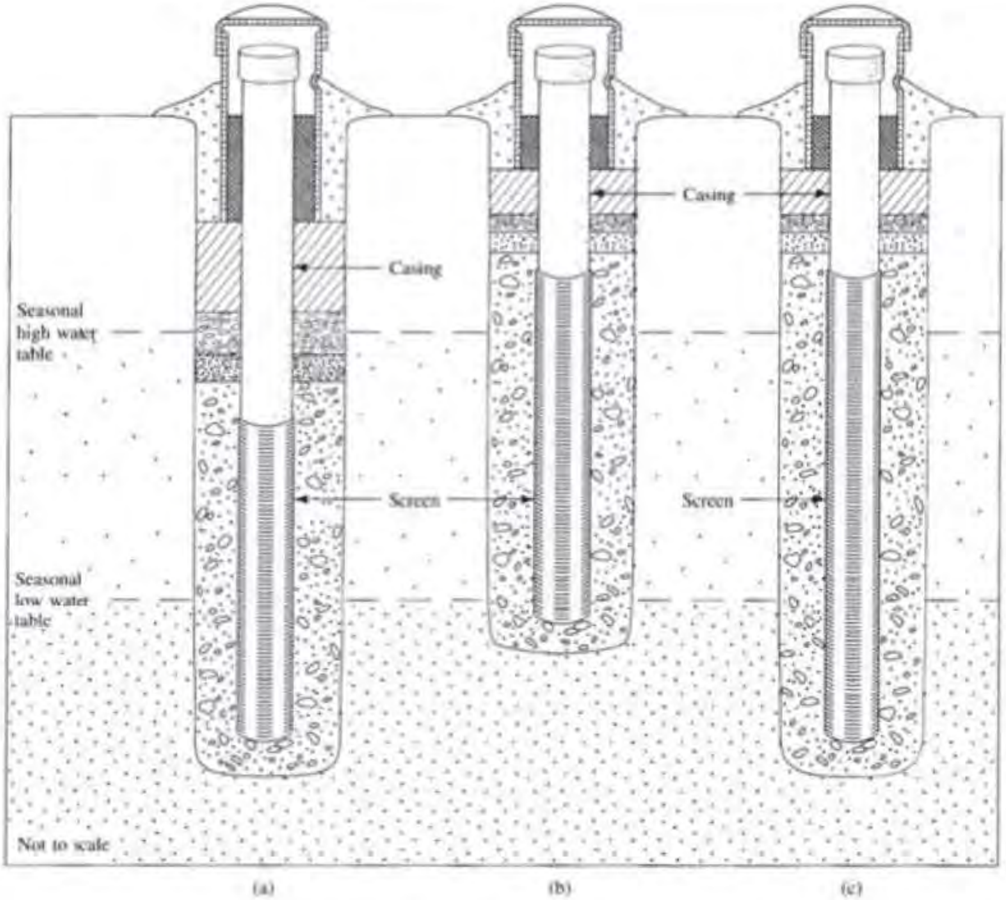
The hydrogeologist must decide on the length of the screen and the depth to which it will be set, based on the objectives of the monitoring program. Objectives could include monitoring the position of the water table, measuring the potentiometric head at some depth in the aquifer, collecting representative water samples from various depths in the aquifer, and detecting both light and dense nonaqueous phase liquids. Moreover, monitoring might be intended to detect the migration of groundwater containing contaminants into an aquifer or evaluating the effectiveness of removing contaminants from an aquifer. All might require different approaches.

To monitor the position of the water table or to detect the presence of LNAPLs, the screen must be set so that it intersects the water table. The screen must be long enough to intersect the water table over the range of annual fluctuation. In addition, the screen must be long enough so that when the water table is at its greatest depth below the land surface, there is enough of the screen remaining below the water table to contain sufficient water for a water sample. A water-table monitoring well will also be able to detect the presence of light nonaqueous phase liquids. In most applications the minimum length of the screen for a water table–monitoring well is 3 m (10 ft) with about 1.5 m (5 ft) above and 1.5 m (5 ft) below the water table. If the water table has more than 1.5 m (5 ft) of annual fluctuation, a longer well screen is needed. However, some governmental guidance specifies a maximum screen length of 3 m (10 ft) or less. Figure 8.10 shows examples of incorrect (a and b) and correct (c) placement of a multipurpose monitoring well intended to measure the position of the water table, detect floating nonaqueous phase liquids, and collect water samples from the upper part of the aquifer.

If the purpose of a monitoring well is to measure the potentiometric pressure at some depth in the aquifer, then the well is called a **piezometer**. A piezometer should have a relatively short screen length, 0.6 to 1.5 m (2 to 5 ft), so that the pressure that is recorded is representative of only a small vertical section of the aquifer. A piezometer can also be used to collect groundwater samples that are representative of a small vertical section of the aquifer.

Monitoring wells utilized to collect groundwater samples should be designed with respect to a specific groundwater monitoring goal. The concentration of groundwater

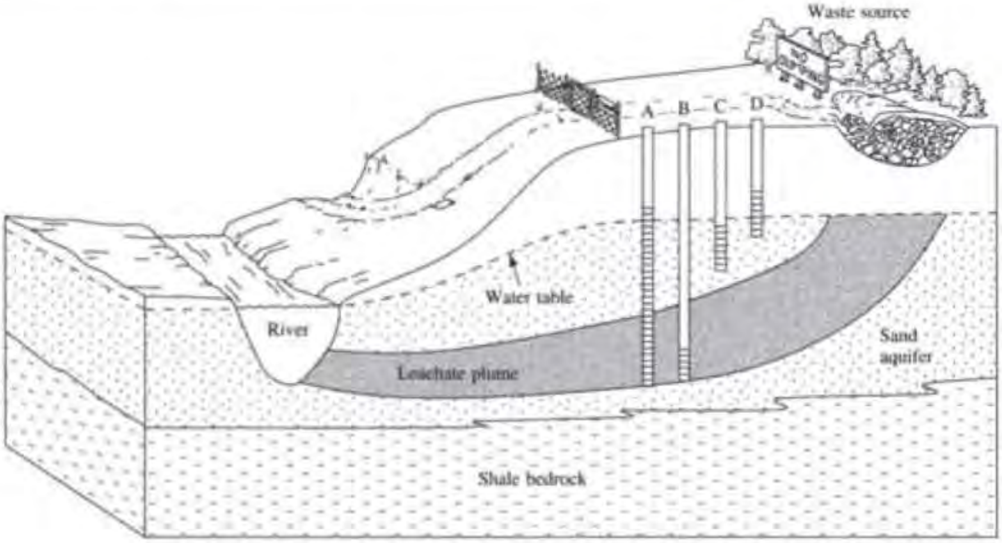
FIGURE 8.10 (a) Incorrect placement of water table–monitoring well screen. Seasonally high water table is above the top of the screen and floating, light nonaqueous phase liquids would be above the screen and not detected. (b) Incorrect placement of water table–monitoring well screen. Seasonally low water table is so far down in well that there is not enough water in well to collect a sample for chemical analysis. (The water table elevation could still be determined.) (c) Correct length and placement of water table–monitoring well screen.



contaminants can vary vertically. If a monitoring well has a long well screen, it has a greater probability of intersecting a plume of contamination. However, a water sample taken from such a well may draw water from both contaminated and uncontaminated parts of the aquifer, resulting in a reported concentration that is less than that of the groundwater in the plume. This is illustrated in Figure 8.11.

The collection of such unrepresentative water samples may have serious implications for the implementation of groundwater regulations. While monitoring groundwater in order to find the actual concentration of contaminants in a plume, it may be necessary to use several monitoring wells or piezometers screened at different depths at the same location (well cluster). Alternatively, several nested wells or piezometers can be placed in a single large borehole, each well with a screened interval and surrounding filter pack at a different depth, and with impermeable grout placed in the borehole between the screened intervals of the individual wells. These clustering and nested techniques can be expensive, not only due to the initial cost of the wells but also due to the costs of multiple chemical analyses for each round of sampling. However, such

FIGURE 8.11 Effect of monitoring well-screen length on water-quality sampling. Monitoring well A is fully screened through the thickness of the aquifer. It intersects the plume of leachate but the reported concentration will be less than the actual concentration as water is withdrawn from both contaminated and uncontaminated parts of the aquifer. Piezometer B is also screened to intersect the plume of leachate. The reported concentration will be representative of the leachate. Piezometer C and water-table monitoring well D don't intersect the plume, indicating that it is deep in the aquifer.



a configuration will yield the greatest amount of information about the hydraulic head as well as the water quality, and is typically a recommended regulatory approach for groundwater monitoring. Additionally, there are multilevel monitoring wells that allow discrete vertical sampling in a single borehole, along with measurement of other hydrogeologic properties such as hydraulic conductivity and fluid pressure (head). Multilevel sampling will be discussed further in Section 8.4.9.

If a monitoring well is intended to serve as a warning that a plume of contamination is escaping from a potential source, then it should be screened in the most permeable parts of the aquifer initially to intercept rapid excursions, with the understanding that measured concentrations may be diluted and not representative of the most contaminated parts of an aquifer. Groundwater, and contaminants that it may be carrying, not only preferentially travel through the most permeable material but travel faster there as well. Hence, the leading edge of a plume of contamination will follow the most permeable pathway.

If the plume of contaminated water is following a zone or direction of high hydraulic conductivity, it may flow in a direction that is not parallel to grad *h*. This may mean that the location of the plume is not exactly down-gradient from the source. (Likewise, as has been discussed in earlier chapters, nonaqueous phase liquids can pool up and deflect off low permeability geologic layers in down-dip directions totally inconsistent with the directions of groundwater flow).

On the other hand, long term monitoring can have different priorities. If an aquifer is contaminated and a monitoring well has been installed to monitor the progress of a remediation effort, the well should not be screened in the most permeable part of the aquifer. Many contaminants can become trapped in low permeability regions, and can become sequestered for long periods of time. The eventual slow release of these trapped pollutants can cause a classically observed "rebound" in aqueous concentrations long after the high permeability zones appear to have been clean. In pump and treat systems, the water will preferentially travel through and flush out the more permeable zones. A well screened in a permeable zone may indicate that the aquifer is rapidly being cleaned, but in fact less permeable zones located nearby may still have high concentrations of contaminants that have yet to be removed. Therefore in contaminant investigations, monitoring low permeability zones is also typically carried out.

In general, the concentration of a solute obtained from a monitoring well will be less than the maximum concentration present in the aquifer. The well screen provides a vertically averaged value of the solute in the aquifer over the length of the screen. If the contaminant plume is thinner than the length of the screen, then the vertically averaged concentration of the solute that is obtained from a monitoring well will be less than the solute concentration in the plume as the monitoring well will be drawing in some uncontaminated water and diluting the contaminated water. Chiang, Raven, and Dawson (1995) found that if a monitoring well is purged continuously for 24 hours prior to sampling, it will draw in uncontaminated water from the aquifer below the well screen, and the concentration of solute in the well could be as much as an order of magnitude lower than the vertically averaged solute concentration in the aquifer.

8.4.8 Summary of Monitoring Design for Single Screened Wells

Figure 8.12 illustrates a comparison of the final design of a water-table observation well and a piezometer illustrating the design elements discussed in this section for single well screen designs.

8.4.9 Multiple-level Wells and Multilevel Devices for Groundwater Monitoring

Because many field studies have suggested that most contaminant plumes exhibit significant concentration changes over small vertical distances (Smith et al. 1987; Dumble et al. 2006; Biswas et al. 2014; USDOE 2015), multilevel monitoring wells (particularly high resolution techniques) often produce orders of magnitude more information and more accurate results than single, long-screened wells. Natural hydraulic gradients within long-screened wells can create vertical flow and cross-contamination within the well, and make definition of the vertical distribution of dissolved contaminants impossible (Reilly et al. 1989; Church and Granato 1996; Elci et al. 2001; Neilsen 2005; McMillan 2014). This message has not gotten through to all municipalities, industries, and regulators, however. The U.S. Nuclear Regulatory Commission (NRC), in its 2003 NUREG 1569 Guidance (pages 5-42 and 5-43) for in situ uranium leaching operations correctly states:

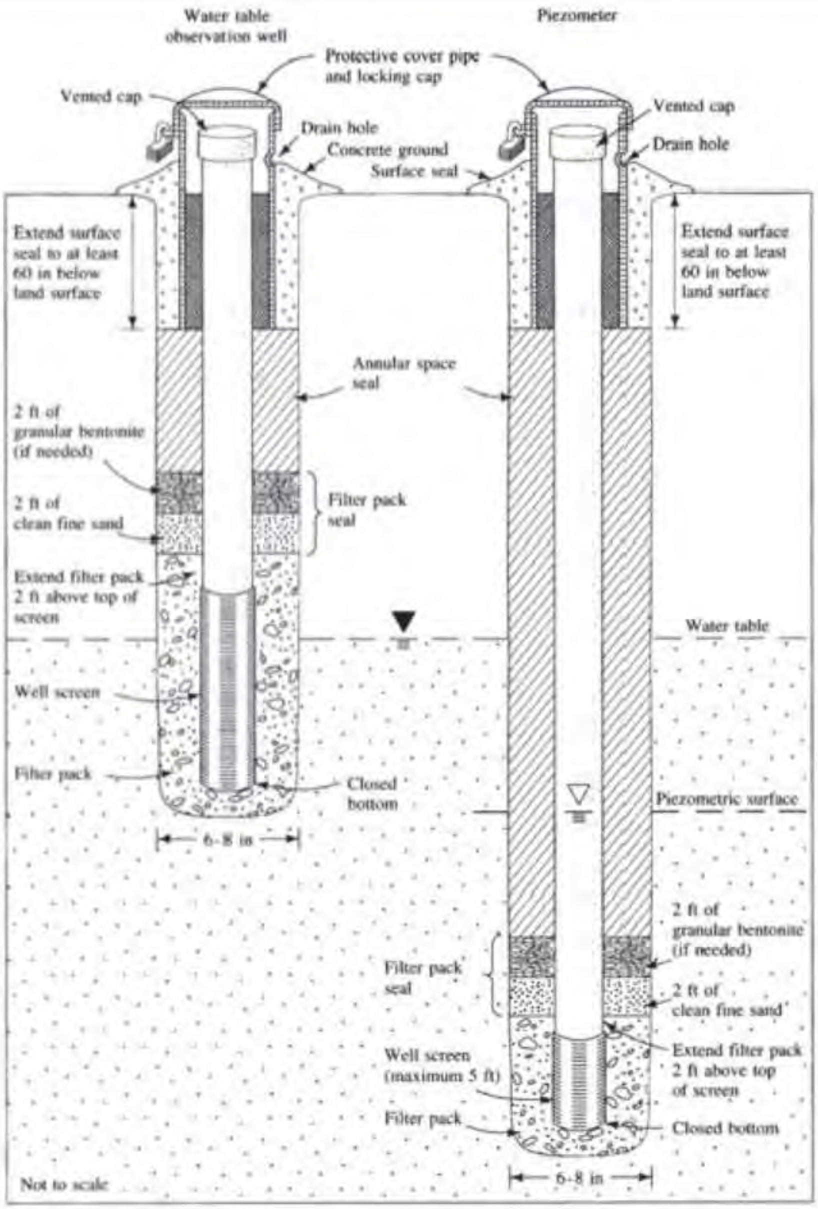
> *"Fully screened monitor wells sample the entire thickness of the aquifer. Therefore, excursions could not pass above or below the well screens. However, the concentration of the indicator parameters might be diluted and therefore may not provide timely warning that an excursion is occurring.*

But then the NRC Guidance continues:

> *"Partially screened monitor wells only sample the zone of extraction within an aquifer. These wells might miss some excursions, but would suffer less from dilution effects than fully screened wells. For most situations the staff favors fully screened monitor wells."*

In this document the U.S. Nuclear Regulatory Commission misrepresents multilevel sampling and does not recognize that high resolution multilevel monitoring: (1) is less likely to "miss" contaminant excursions than wells screened the entire aquifer

FIGURE 8.12 Construction details of a water-table observation well and piezometer.

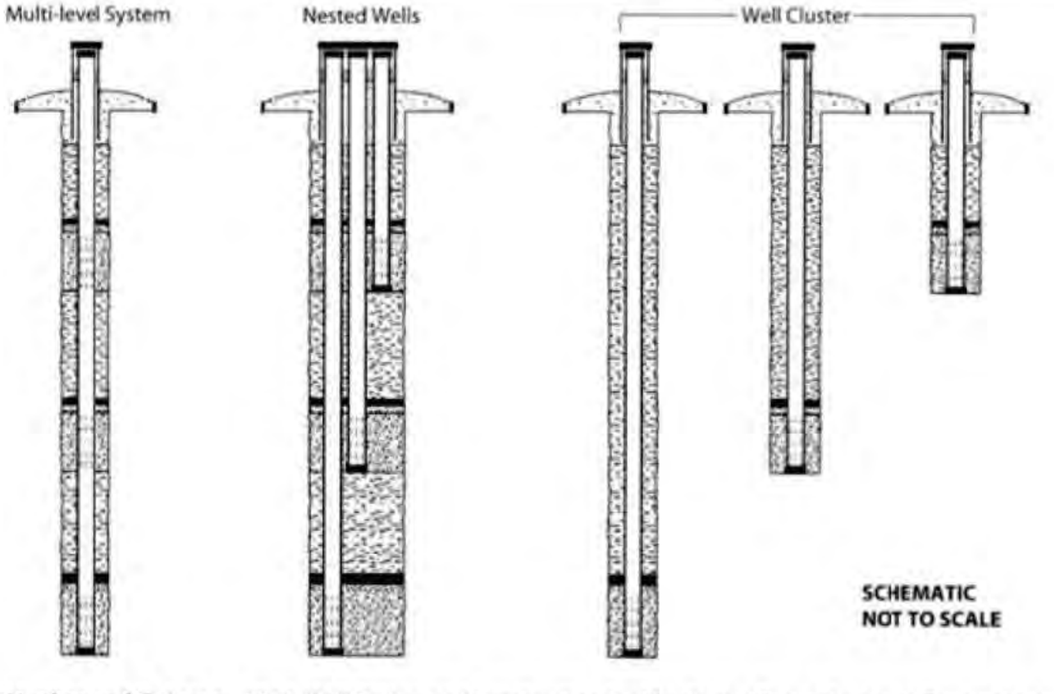


Source: Wisconsin Department of Natural Resources.

length, (2) has more possibility of accurately intercepting and quantifying excursions without bias, (3) reduces the possibility of contaminants migrating vertically within a monitoring well, (4) is many times more useful in post-mining remediation and site stabilization (both in directing cost-effective cleanup efforts and documenting their success), and (5) is much more protective of public health and ecological well-being.

Nested and Clustered Wells As mentioned in Section 8.4.7, to reduce dilution effects of long-screened wells and to preserve vertical sampling integrity, usually monitoring wells are installed in nested or clustered configurations (also called "multiple completions"), or with other types of multilevel sampling devices in a single borehole. Figure 8.13 illustrates multilevel sampling systems, nested wells, and well clusters. For nested wells, there is typically a single large borehole with several piezometers or wells placed in the same hole with screened intervals at different depths below the water table and with grout separating each different sampling depth. There has been some concern with the integrity of grout sealants in nested wells, and some criticism has been leveled at using these nested configurations. This is because of the difficulty in achieving effective and impermeable grout layers. These problems can be significant where the grout layers are thin because of many vertically close-spaced screen and grout intervals, or where there are many casing riser pipes in the nested well requiring grout to be placed effectively between the many pipes without void spaces developing. Clustered well groupings, on the other hand, sample different depths at the same locality by having several, closely spaced monitoring wells or piezometers with each in its own individual borehole. These individual wells typically can be placed within 1.5 m

FIGURE 8.13 Multilevel sampling systems, nested wells, and well clusters with above ground completion.



Source: E. Hughes and G. Aarons. 2014. *Well Design and Construction for Monitoring Groundwater at Contaminated Sites*. The California Environmental Protection Agency.

(5 ft) of each other. Under these circumstances it is possible to obtain an excellent seal to prevent vertical movement of water along the casing.

In nested wells, two or more monitoring wells or piezometers are placed in a large-diameter borehole with grout seal between screened intervals at different depths. For example, this could be done in an unconsolidated formation by (1) driving a 25.4 or 30.5 cm (10 or 12 in.) diameter casing with a cable tool rig to the depth of the bottom piezometer, (2) installing the deepest piezometer, (3) pulling back the casing and installing the filter pack and seal for the deepest piezometer, (4) pulling back the casing and grouting up to the level of the next piezometer, (5) allowing the grout to harden, (6) installing the next piezometer, (7) pulling back the casing and installing the filter pack and seal for the second piezometer, and (8) pulling back the casing and grouting up to the level of the third piezometer, etc.

Simple Manufactured Multilevel Samplers It is possible to install inexpensive multilevel sampling devices in a sandy aquifer. One early manufactured model of such a device consists of a rigid PVC tube, inside of which are multiple tubes of flexible tubing. Each tube leads from the surface and ends at a different depth. Each has a port into which a groundwater sample can be drawn. Sampling ports can be closely spaced vertically, so that very detailed vertical sampling can be accomplished. Water is withdrawn from the tubing by applying suction, so the water table had to be less than 7.6 m (25 ft) below the surface in these simple early multilevel sampling wells. These rudimentary methods include a variation by fastening a bundle of flexible tubes, each of a different length, to the outside of a rigid PVC pipe that acts as a spine. Several types of simple manufactured multilevel samplers have been developed (Pickens et al. 1978; Cherry and Johnson 1982; Ronen et al. 1986).

Barker et al. (1987) evaluated the bias in samples that can be introduced by the use of multilevel piezometers constructed out of flexible tubing. Leaching of plastics from the plastic tubing is one problem. Another problem is the sorbing of organics by the tubing. Both these problems can be minimized by using Teflon® tubing and thoroughly purging the tube prior to sampling, although Teflon® is porous and can have some minimal memory effect. Many types of flexible tubing can actually transmit organics from groundwater through the tubing wall to the sample water in the tubing. This is especially true for polyethylene tubing. Samples drawn from below an organic plume may indicate contamination, when in fact the organics are being transmitted across the plastic tubing from adjacent contaminated groundwater. This can apparently occur even with Teflon® tubing. For this reason, multilevel piezometers, designed so that the flexible tubing is exposed to groundwater, may not be appropriate for monitoring plumes of organic contaminants. If the flexible tubing is contained within a casing, such as in Figure 8.14, this should not be an issue because the tubing doesn't come into contact with the groundwater.

A simple multilevel sampler can be installed by using a hollow-stem auger. The device is constructed at the surface and lowered to the desired depth through the augers. It is not possible to develop the sampling ports, so this device is best suited for clean, sandy sediment. No filter pack or grout is used in this very simple construction. The augers are withdrawn and the native sand is allowed to slump around it. One disadvantage of this device is that it is usually not possible to measure water levels with it.

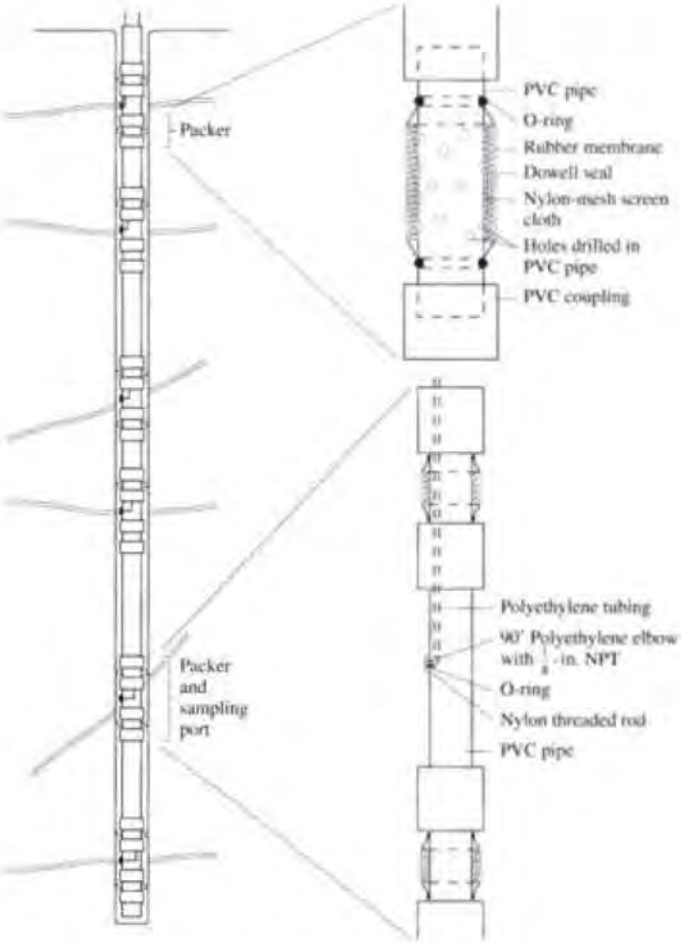
generally expensive, these multilevel wells have advantages of allowing fewer wells and subsurface disturbance at each site, collection of fluid samples without repeated purging, prevention of vertical flow within the borehole, less possibility of cross contamination with discrete depth sampling, and options for automated sampling at any number of multiple depths in a single well.

Flexible Liner Systems Another type of multilevel sampling practice employs the flexible liner system (developed by FLUTe™) and represents a significant advancement over a simple multilevel system. Similar to the simple system above, it has a series of internal tubes inside a liner which allow sampling and pressure measurement at selected intervals down hole in uncased wells. In hard rock consolidated systems, downhole television logging in uncased boreholes can identify exact locations of fractures (and other depths of interest) and tubing can be customized to sample those depths. In this system, a flexible polyurethane–coated, nylon fabric liner is emplaced with eversion (turning inside out) from a shipping reel. The liner is pressurized (pneumatically or hydraulically), inflated, and extends downward from internal pressure head. The liner deploys from the ground surface downward, creating a sealing pressure that prevents vertical flow outside the liner, and has tubing (usually made of polyvinylidene fluoride—PVDF) inside the liner from ground surface to vertically displaced subsurface ports. The system is versatile in that the inflating liner can be placed in boreholes that change direction due to directional drilling, and can move in varying diameter boreholes, such as narrow, shallow surface casing to wider uncased sections below, or narrowing or telescoping boreholes. Interestingly, this system can be modified to measure discrete depths of nonaqueous phase liquids (NAPLs) by use of a hydrophobic "ribbon" sampler. In this application, a porous, continuous, hydrophobic sleeve, that is impregnated with a powdered oil dye (Sudan IV), is deployed concurrently on the outside of the flexible liner. The hydrophobic material readily "wicks" NAPLs and when retrieved identifies depths of NAPL contamination. The hydrophobic sleeve is replaceable for additional deployments on the same flexible liner (Riha et al. 2000; USEPA 2004).

Packer Systems A type of multilevel sampler optimal in bedrock boreholes involves straddle packers, which when inflated isolate a section of a borehole for hydrological testing and sampling. In this design (Figure 8.15) packers are located above and below each sampling port; when they are inflated, they seal off that part of the borehole and are particularly effective in segregating individual fractures or groups of fractures for analysis in uncased boreholes. Packers can also be used within well casing in less consolidated material. Packers can be permanently installed, or they can be removed and reused if desired. Though designs vary, the inside of a typical single packer is a perforated pipe forming the inner packer body, covered with a porous plastic sleeve and an expansion sleeve. External to that is a gum rubber inner sheath, often enveloped in woven Kevlar® and encased in a durable gum rubber outer sheath, with the assembly secured on either end with stainless steel clamps. One type is the Solinist® Waterloo System with includes multi-purge manifold well heads and dedicated sampling pumping and transducers.

Interesting specialized variants of packer systems have been constructed for specialized applications. Packers have been used in small, bedrock boreholes in conjunction with seals created by injecting grout into a flexible cylindrical impervious fabric liner. These liners have a diameter slightly larger than the borehole, ensure that the

FIGURE 8.15 Multilevel groundwater sampling device for use in fractured rock aquifers.



Source: J. A. Cherry and P. E. Johnson. 1982. A multilevel device for monitoring in fractured rock. *Groundwater Monitoring & Remediation* 2:41–44 Used with permission.

entire borehole above a screened interval is sealed, and prevent grout from entering fractures and altering groundwater chemistry (Parker et al. 2015; Pierce et al. 2015).

■ 8.5 Installation of Monitoring Wells

8.5.1 Decontamination Procedures

Because the purpose of drilling a monitoring well is to collect a sample of water and analyze it for very small concentrations of chemicals, it is highly desirable not to introduce any chemicals into the aquifer as a part of the well-drilling and installation procedure. The process of cleaning the equipment and supplies that will be used is called **decontamination**.

When materials are manufactured, they may become coated with substances such as grease and oil. Therefore, unless the manufacturer specifically guarantees that the article has been decontaminated and has shipped it in a well-sealed wrapper, it should be decontaminated. Equipment that has been used at a contaminated site should be assumed to be contaminated and should be decontaminated before it is used at another site. Even at the same site, if a drill rig or a bailer is used at different wells, decontamination is required to prevent cross contamination (contamination from one area being introduced into a clean area) that could occur.

There is wide variability in required and recommended decontamination procedures in the United States between the USEPA and the various states (Mickam et al. 1989). The hydrogeologist must consult with the appropriate regulatory authority to determine if a specific decontamination procedure is required. In the absence of a specific requirement, the following generic procedure should adequately clean equipment and supplies. In some cases not all the steps are required. For cleaning large equipment such as a drilling rig, a specific area must be set aside and a decontamination pad must be constructed to capture all the fluids used in the process. If the rig is contaminated, wash water from it may also become contaminated. Be careful that any solvents used aren't accidentally released to the environment. Small tools such as bailers and Shelby tubes can be cleaned in buckets set on a polyethylene sheet. Sampling pumps can be cleaned by running various wash solutions through them, as well as washing the exterior.

The following steps are used to clean drilling and soil sampling equipment including drill rig, augers, drill rod, tools, sampling tubes, etc.:

1. Use a wire brush or similar equipment to remove all dried sediment and thick accumulations of grease.
2. Wash the equipment with a soft brush and water with phosphate-free detergent.
3. In extreme conditions organic residues can be removed by washing the equipment with an organic solvent such as methanol or propanol. Don't use solvents such as trichloroethene that might be expected to be found at a hazardous waste site.
4. Clean and rinse the equipment with potable water.
5. Rinse the equipment with deionized water.

Steam cleaning with a pressure sprayer can be used in step 4 for equipment that can withstand the heat and force of the spray. After equipment has been decontaminated, it should not be placed on the ground. It can be wrapped in clean paper or aluminum foil or set on polyethylene sheets.

Sampling equipment should also be decontaminated between uses. If the equipment has not come into contact with nonaqueous-phase liquids, rinsing with potable water and washing thoroughly with phosphate-free detergent, including scrubbing the inside of tubes with a bottle brush, followed by a potable-water wash and then a deionized-water rinse, should suffice. If the equipment has come into contact with nonaqueous-phase organic liquids, then an initial solvent wash may be necessary.

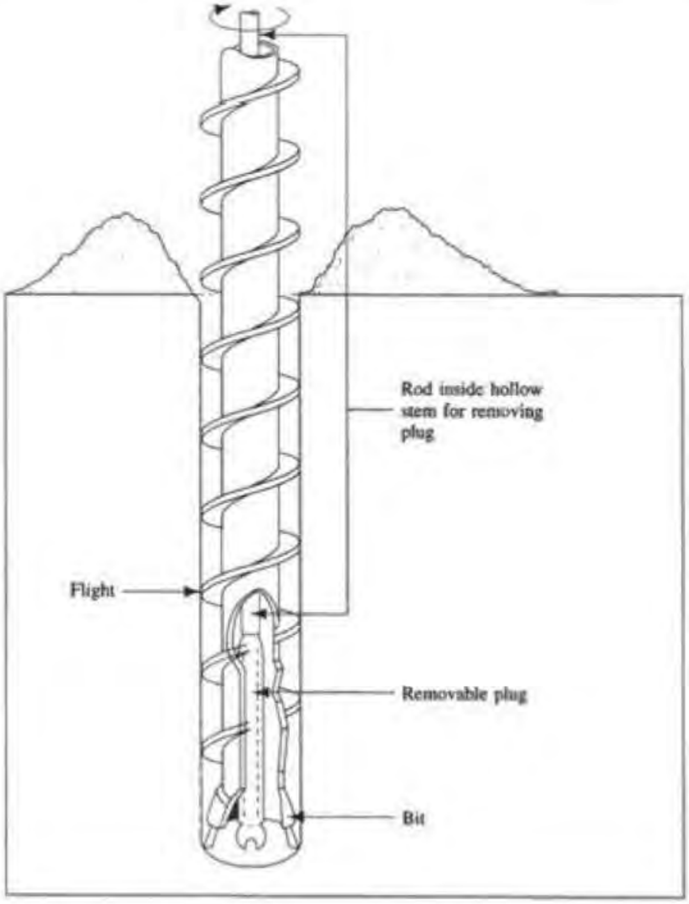
The cost of decontamination of sampling equipment and the uncertainty introduced by solvent washing has led many hydrogeologists to specify dedicated sampling equipment in each well. Disposable bailers are also available that are less expensive than the cost of labor involved in cleaning reusable bailers.

8.5.2 Methods of Drilling

There are a number of methods of drilling that are appropriate for installation of monitoring wells. When working in shallow unconsolidated formations, hollow-stem augers are commonly used. If a well is to be drilled deeper than about 30.5 m (100 ft) or into bedrock, a rotary drilling method may be appropriate. Cable-tool drilling is an excellent way of installing monitoring wells in both unconsolidated and consolidated formations, but it is slow and may be expensive. Hollow-stem augers with a bit that contains carbide teeth can also be used in weak, indurated rock. Newer techniques include sonic drilling and directional drilling.

Hollow-Stem Augers Hackett (1987; 1988) presents an authoritative discussion of all aspects of drilling with hollow-stem augers. A hollow-stem auger looks a little like a large, untapered screw (Figure 8.16). The auger flights are constructed around a hollow pipe. A drilling rig rotates the augers and a bit on the end of the auger loosens the sediment, which is then brought up to the surface by the rotating auger flights. The cuttings accumulate at the surface and must be shoveled away from the augers. Figure 8.17 pictures an auger-drilling rig. The auger is advanced into the ground as it is rotated. A plug on the end of a rod inserted through the hollow-stem may be screwed into the bit to seal the end of the opening and prevent sediment from coming up inside the hollow-stem. Alternatively, a nonretrievable plug can be placed in the end of the

FIGURE 8.16 Hollow-stem auger drill rod and bit.



Source: M. L. Scalf et al. 1981. *Manual of Ground Water Sampling Procedures*. National Water Well Association. Used with permission.

FIGURE 8.17 Hollow-stem auger drilling rig.

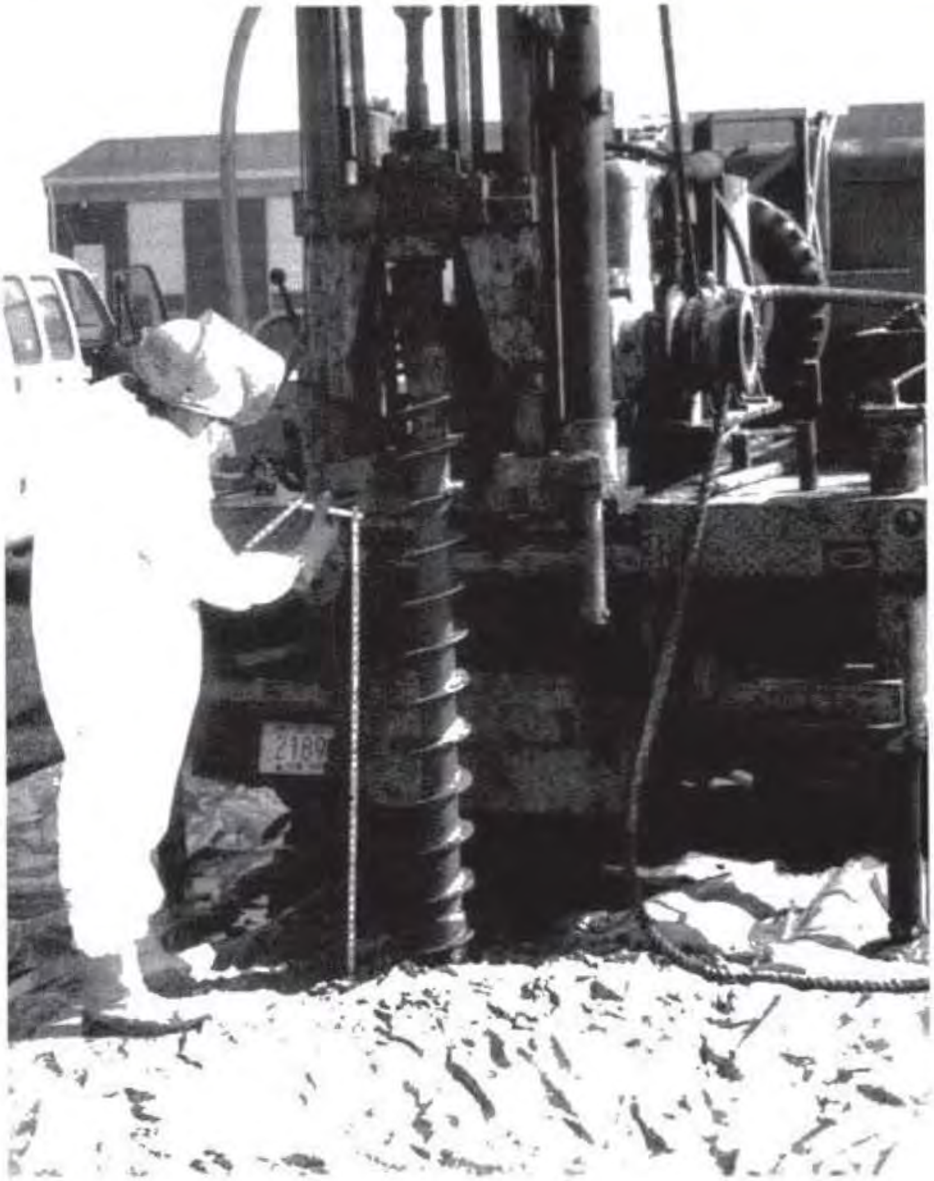


Photo credit: C.W. Fetter.

bit. This plug is knocked out of the end of the augers when the final depth is reached and it is no longer needed. However knock-out plugs preclude the collection of soil and water samples during drilling.

One advantage of drilling with hollow-stem augers is that drilling fluids and mud are normally not required. Circulation of drilling fluids has the potential to spread contaminants throughout the borehole. Drilling mud is a viscous liquid needed in mud-rotary drilling that can line the borehole and partially seal it. However, when drilling in formations with cohesive layers, the auger bit may smear clay from the cohesive layers so that it mixes with sand and gravel layers at the perimeter of the borehole. Auger drilling typically can advance about 15.3 to 30.5 m (50 to 100 ft) per day if samples are being taken. Occasionally, downward progress can cease if a large cobble or boulder is encountered (called auger refusal).

Augers usually come in lengths of 1.5 m (5 ft). One flight is advanced into the ground and then the drill stem is disconnected and another flight is attached to the augers in the ground. At this time samples of the formation ahead of the auger bit may be taken. The plug on the end of the bit must be removed before sampling can occur. The maximum depth at which hollow-stem auger drilling can normally be used is 45.8 m (150 ft) (Hackett 1987); as a practical matter, it rarely exceeds 30.5 m (100 ft).

Some loosely consolidated sands, called heaving sands, can enter into the borehole when the plug is being removed. This problem can be avoided by keeping the hollow stem filled with potable water when the plug is removed. The potable water should not contain any contaminants that might be found in the groundwater. If no formation sampling is planned, then a knock-out plug can be used to prevent the introduction of heaving sands into the hollow-stem during drilling. The knock-out plug can be removed after the final depth is reached by pushing down with the well casing if it is stainless steel; otherwise it will be necessary to use a rod prior to the time that the well is installed.

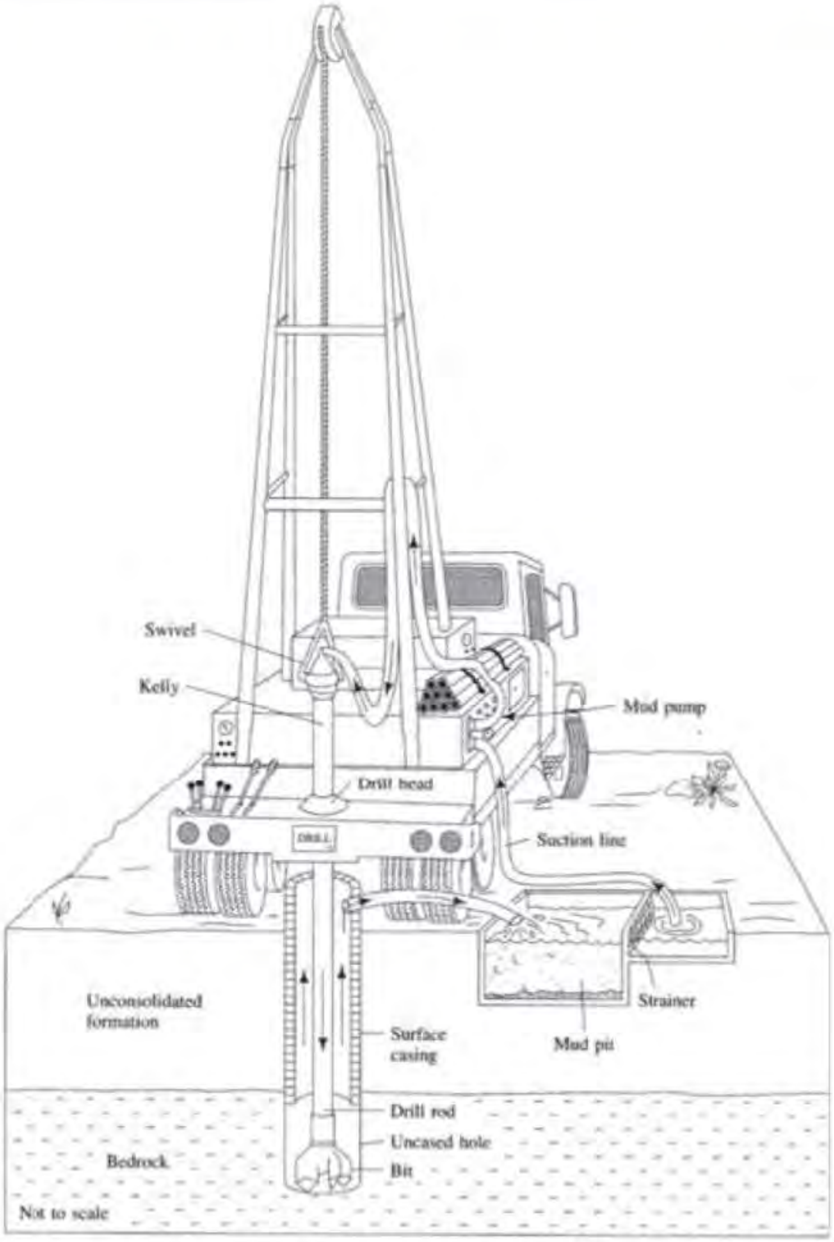
Hollow-stem auger drilling can also be used to sample water quality at various depths during drilling. At a selected horizon the plug at the end of the hollow stem is removed. A well point on the end of a rod is lowered to the bottom of the augers and then is driven ahead of the bit by hammering or hydraulic pressure. The well point is developed by pumping until clear water is obtained. A sample of groundwater at that depth is then obtained. It is best if potable water is not used in the borehole during this procedure, because it could interfere with the groundwater quality. If there is heaving sand inside the augers, the well point can be driven through it. Alternatively, a slotted hollow-stem auger can be used (sometimes called a screened hollow-stem auger or Keck auger) which allows water to flow into the stem.

Keeley and Boateng (1987) suggested a modification of the hollow-stem auger drilling technique, in which a temporary casing that is larger in diameter than the auger bit is employed. The auger is advanced several feet and then the temporary casing is driven to the depth of the auger bit by repeatedly dropping a heavy weight on the top of the casing. The advantage of this modification is that it prevents mixing of soil horizons as the augers rotate.

Mud-Rotary Drilling Mud-rotary drilling can be used in both unconsolidated and consolidated formations. It is fairly rapid, up to 30.5 m (100 ft)/day, and can be used to depths far in excess of most that might be required for groundwater-contamination studies. A heavy drilling fluid, made by mixing various additives to water, is circulated in the borehole by pumping it down the inside of hollow drill rods. The mud rises back to the surface in the annular space between the borehole wall and the drill pipe. The rising mud carries with it the drill cuttings, which settle out in a mud tank at the surface. Figure 8.18 shows the circulation pattern for mud-rotary drilling. Alternately, reverse circulation is often used where drilling fluid goes down the annular space and returns upward through the drill pipe (opposite of Figure 8.18). This method, discussed below, can allow greater upward velocities and larger, heavier cuttings can be retrieved.

One advantage of mud-rotary drilling is that the borehole will remain open after the string of drill pipe and the bit are removed. This means that a complete suite of geophysical logs can be run on the hole, which is kept open by the weight of the mud

FIGURE 8.18 Circulation of drilling fluid in mud-rotary drilling.



inside it. However, the fluid in the drilling mud can penetrate the native formations and alter the groundwater geochemistry. The coating of drilling mud on the borehole walls may be difficult to remove. This can impede the hydraulic connection between the well and the formation. Bentonite-based drilling muds may remove metals from the groundwater and affect the chemistry. Certain additives to drilling mud can also be problematic from a water quality standpoint. Because of the potential problems with drilling mud, rotary drilling may not be as suitable for groundwater contamination studies as hollow-stem augers. However, under many hydrogeologic conditions it is the only drilling method that is practical. Good well development to remove the residual drilling mud in the screen zone is very important

Air-Rotary Drilling If the monitoring well is to be installed in bedrock, then air-rotary drilling may be considered. First a surface casing needs to be installed through any unconsolidated material. Typically this is done by using mud-rotary drilling. The surface casing is large enough that the air-rotary bit can fit inside of it.

The fluid used in air rotary is compressed air, which is blown down the inside of the drill pipe. The air then blows the cuttings back up the annular space, where they accumulate around the borehole. When the water table is encountered, the air may blow groundwater out of the borehole as well. If this occurs, it is possible to determine when the water table is encountered and the relative yield of the well. However, the air may also force the water back into the formation. Air-rotary drilling using a down-hole percussion bit can drill up to 18 m (60 ft)/hr. Samples are collected as chips, which are brought to the surface with the return flow of air and water.

Air-rotary drilling is fast and can go to depths of a thousand feet of more. Because air is the drilling fluid, contamination problems are minimized. However, the drillers may want to add a foaming agent to the air (air/polymer mix) as it goes down the hole. The foam helps to float the chips to the surface, but it consists of organic chemicals such as isopropyl alcohol, ethyl alcohol, and alcohol ether sulfate, and its use should be avoided. The air compressors have air filters, which need to be in good working condition; otherwise, lubricating oil and other contaminants may be introduced into the borehole with the compressed air. Percussion hammers used for air-rotary drilling may also need lubricants.

Air-rotary drilling may introduce volatile organic compounds into the atmosphere as well as blowing contaminated dust out of the borehole.

Reverse-Rotary Drilling In reverse-rotary drilling the circulating drilling fluid drains down the annular space and then is pulled up the center of the drill stem by a suction pump located on the drill rig. Because the drilling fluid rises with a much greater velocity in reverse-rotary than in mud-rotary drilling, a much less viscous drilling fluid is used. In many cases clear water mixed with the drill cuttings is all that is necessary. This gives the reverse-rotary method an advantage over mud-rotary drilling, since it is much easier to develop the well because there is no mud wall on the borehole to break down. However, reverse-rotary drilling is more expensive than the mud-rotary method, and the minimum borehole diameter is 30.5 cm (12 in.)

Cable-Tool Drilling Cable-tool drilling is one of the oldest drilling methods and has been used widely for the installation of water wells. Although the drilling equipment is less expensive than for some other methods, the drilling is slow and overall costs may be expensive due to high labor costs.

In cable-tool drilling a heavy bit is located at the end of a tool string hanging from a cable. The drill rig repeatedly lifts and drops the hammer, which breaks up consolidated rock or loosens unconsolidated sediment. A steel casing is driven into the formation behind the bit. When the bottom of the casing fills with broken rock and sediment, the tool string and bit are removed, and a bottom-loading bailer is used to remove the accumulated cuttings. Below the water table, the groundwater and cuttings make a slurry. Above the water table, water must be added to make a slurry so that the bailer can be used. Drive casing is needed only until bedrock is reached. In most bedrock formations the hole will stay open without drive casing. Figure 8.20 shows the tools used for cable-tool drilling.

Advantages of cable-tool drilling include the fact that no drilling fluids are used and that nothing is circulated through the well. Both factors serve to limit contamination problems. It is easy to collect representative samples of the formation during bailing of the casing. Well points can be driven ahead of the casing in unconsolidated formations for the collection of water quality samples. Cable-tool drilling can be used to depths in excess of 305 m (1000 ft). This method however can be extremely slow for deep boreholes, as the tool string and bit must be removed from progressively deeper depths to allow insertion of a bailer for the removal of cuttings, the bailer must then be removed from depth, and the tool string and bit reinserted. As depths increase the time required for this process compounds.

Sonic (Vibratory) Drilling Sonic drilling uses high frequency mechanical oscillation with rotary motion to fluidize subsurface material. As soils and formational materials experience liquefaction, temporary porosity reduction and inertial effects reduce friction on the drill string and drill. The destroyed shear strength of the subsurface formations allows rapid downward advancement in most instances. Advantages include a minimal amount of formation disturbance, reduction of drill spoils and waste compared to other methods, the method can produce continuous cores, sonic does not require circulating drilling fluids, and it can be converted to air or mud rotary or cable tool percussion techniques. Its disadvantages are that the technique is not as readily available as other techniques and is generally more expensive initially.

Other Types of Drilling Other types of drilling include percussion rotary air blast (RAB), air core drilling, and diamond core drilling. RAB combines rotary fluid circulation with the percussive impacts of a pneumatic, reciprocating, piston-driven "hammer" to pulverize rock. This is an effective way to advance drilling downhole in consolidated rock and mixed consolidated/unconsolidated terrain. Like most rotary fluid circulation techniques, circulation can be lost if a large cavity is encountered such as caverns in karst areas, lava tubes in volcanic regions, or human-made features such as subsurface mine shafts. Air core drilling cannot penetrate consolidated rock as well as RAB; it normally is used on weathered regolith or other unconsolidated material. The air core method utilizes hardened steel or tungsten blades to cut into the ground, and collects a more representative sample of solid material compared to RAB. Diamond core drilling is a very slow method used in hard, consolidated rock. It produces a rock core that can be inspected. Often fracture patterns, fracture orientation and aperture size can be determined from these cores. Diamond coring for short intervals can also be used on smaller consolidated formations encountered while drilling with other methods.

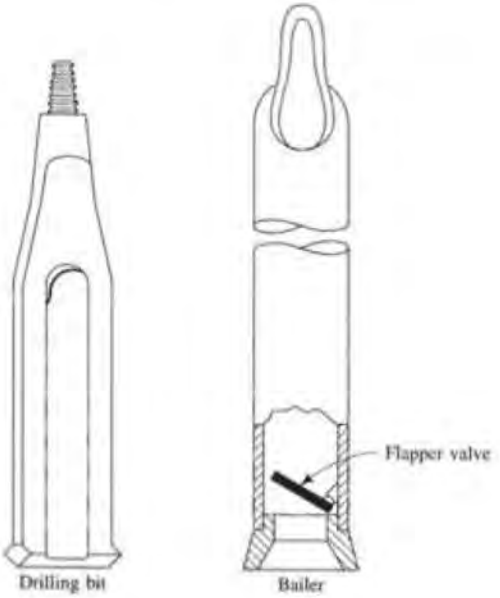
When drilling in areas with muddy or spongy soils, it may be necessary to build temporary roads, e.g., laying down a layer of crushed rocks to permit the heavy drilling equipment to reach the drilling locations without getting stuck (Figure 8.19). Alternatively, portable coring drilling machines, originally designed for mineral exploration, can be used to advantage to install hard rock monitoring wells in sites that are hard to access, in remote locations and wilderness sites, and in eco-sensitive areas. Drills, such as the Shaw Portable Core Drill and the Winkie Drill can produce small diameter holes amenable to fractured rock monitoring (Parker et al. 2015).

FIGURE 8.19 When drilling in difficult-to-access areas or where soggy soils prevent heavy drill equipment to reach the site, a portable drill rig can be used. Shown here is the installation of an 8-inch bedrock well with a portable air-rotary drill rig in a rice field in Goa, India. The drill rig is powered by pneumatic pressure provided by a truck-mounted compressor which is safely stationed on hard ground approximately 100 m (300 ft) away.

Photo credit: T. B. Boving.

Directional Drilling Directional drilling involves the placement of nonvertical boreholes. Most of the above drilling methods are able to be used in slant drilling (excepting cable tool), where in the simplest application, the mast or drill rig tower is tilted and drilling proceeds at an angle. This modification allows great horizontal access under structures such as buildings, landfills and highly contaminated areas. Drilling through a subsurface NAPL pool, for example, can be avoided in some cases. Traditional drilling methods can be difficult to control in slant drilling because of unwanted deflection, as in slant auger drilling. As slant auger drilling proceeds, cuttings which fall on the bottom side of the hole can eventually force the bit upward into a more horizontal line.

FIGURE 8.20 Tools used for cable-tool drilling.



Controlling wellbore trajectory has become more of a refined technology in recent years. Most modern directional drilling begins in a vertical direction until a desired kick off point where the well inclination is changed using drilling motors and rotary steerable systems. While the use of directional drilling is much more common in oil and gas development, its applications to contaminant hydrogeology are plentiful, particularly where surface or near-surface features or contaminant hotspots must be avoided, but geologic, hydrogeologic, and contaminant information from greater depths directly under these areas is needed.

8.5.3 Drilling in Contaminated Soil

When drilling at a contaminated site, the cuttings that are brought to the surface may be contaminated. Drilling personnel should wear appropriate protective clothing and, if necessary, use breathing apparatus. A large, heavy sheet of plastic should be placed in the work area, and the drill bit should be advanced through a hole in the center of the plastic sheet.

The cuttings augered to the surface can be collected from the plastic sheet and put into containers for proper disposal.

8.5.4 Sample Collection of Solid Material During Drilling

Samples of unconsolidated materials and rock are needed to delineate the geology of a site. They are collected by drilling **borings**. Borings may be made just for sample collection, or they may be made as a part of the process of installing a monitoring well. Borings may be made by any of the methods of drilling discussed in Section 8.5.

During the drilling process, earth materials are brought to the surface. During the augering process, soil and sediment ride up the augers; in the mud-rotary process, earth materials come up mixed with the mud; in air-rotary drilling there is a slurry of rock and water brought to the surface by air pressure; and cuttings are brought to the surface with a bailer in cable-tool drilling. In all cases the samples are disturbed, some (such as the samples on the augers) more than others. In addition, it may be difficult to tell the exact depth represented by the sample. Fine layering of sedimentary materials cannot be distinguished in such samples. An imprecise model of the geology can be constructed from these samples, but for more details, undisturbed samples should be collected.

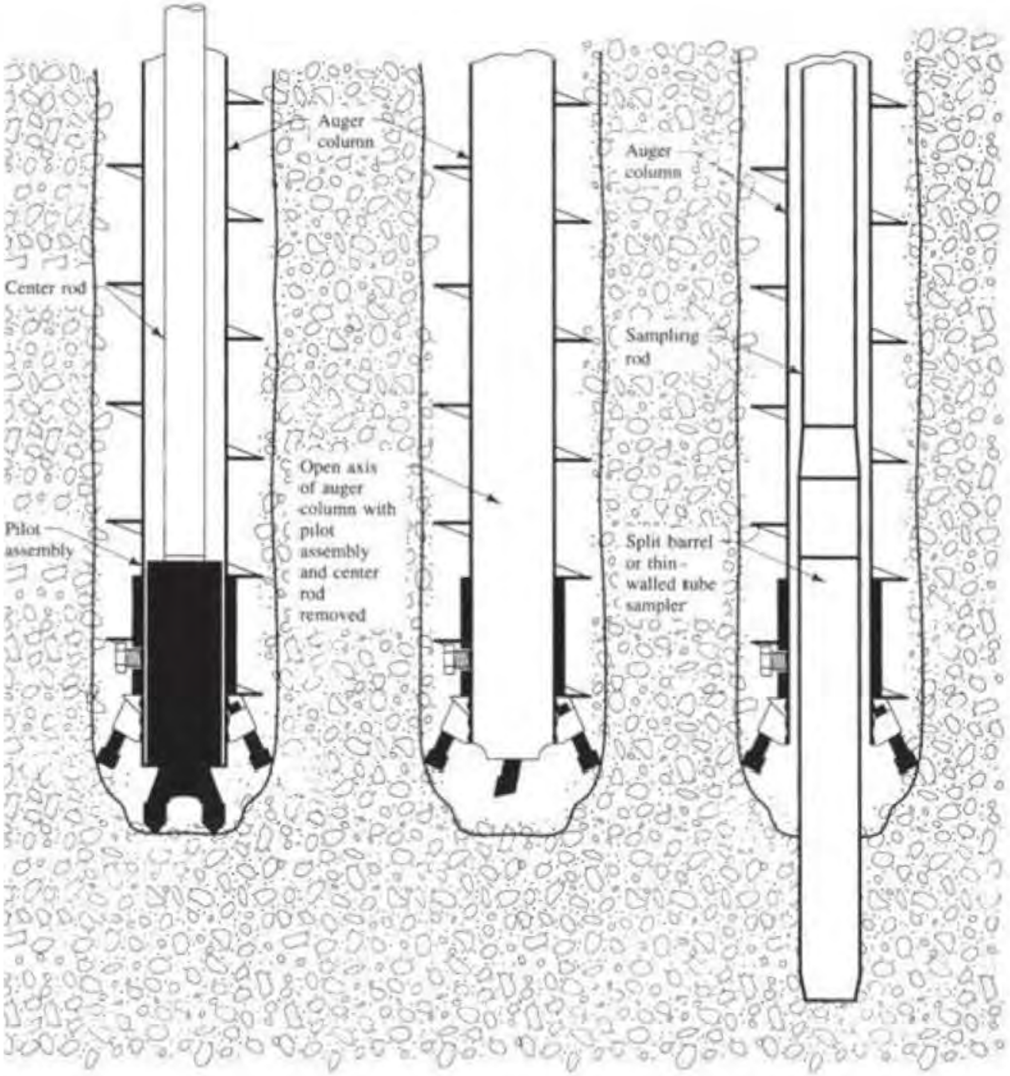
A **core sample** is collected for consolidated material by obtaining a **rock-core sample** with a special drilling bit studded with industrial diamonds as mentioned above, or for unconsolidated material with special sampling tubes that are driven into the unconsolidated formations. Interpretation of hard rock cores in consolidated, fractured media suspected of contamination has become quite advanced in the last few decades and can include field geologic core analysis, and laboratory analysis (Parker et al. 2012). The initial field analysis involves determination of the number of fractures, fracture orientation and aperture size, and fracture porosity measurement. This analysis can also observe any occluding chemical precipitates filling (or "healing") the fractures. The orientation of fractures from several core holes can be analyzed to give a three-dimensional view of fractures at a site. Combined with downhole geophysics and tomographic methods, field data can give considerable insight into a fractured rock media and the potential for contaminant movement.

Laboratory measurement of bedrock cores can quantify contaminants in the core, simulate degradation microcosms, and provide core physical, mineralogical, and microbial measurements to determine contaminant phase and mass distribution. Typically, most groundwater flow in fractured consolidated rock occurs through interconnected networks of fractures and secondary porosities, surrounded by low permeability blocks of rock. In adjacent blocks with porosity greater than 1% however, particularly in sedimentary rocks, an appreciable mass of a contaminant can move into the rock matrix. This matrix diffusion in low-permeability blocks or effectively reduces the mass flux in the surrounding fractures (Parker et al. 1997; Parker et al. 2010; Kennel 2008).

Great care must be exercised in the interpretation of rock cores or unconsolidated borings, particularly in the measurement of subsurface contamination or characterization of stratigraphy based on just a few samples. The absence of contamination in a core could be the result of preferential flow (also called "funneling," "fingering," wetting front instabilities, or Rayleigh Taylor instabilities), allowing contamination to completely bypass a boring but still be present in massive amounts. Likewise, unwarranted extrapolation of meager stratigraphic data, particularly assuming continuous layers of unvarying properties, is a common problem particularly in situations where incomplete site characterization goes unchallenged. There are two main types of sampling tubes for unconsolidated samples. Both types of tubes can be used with hollow-stem augering and mud-rotary drilling if the drill rod and bit have a provision for a sample tube to be extended through them into the formation ahead of the bit. Figure 8.21 shows the sequence for the extension of a sampler through the end of the bit of a hollow-stem auger. The sampler is driven or pushed into undisturbed formation ahead of the bit. In cable-tool drilling the drill bit is removed from the borehole and the sampler is lowered on a rod or cable.

A **Shelby tube** is a thin-walled tube that can be screwed to the end of a rod, lowered to the bottom of the drilled hole, and pressed into cohesive sediments by using hydraulic pressure reacting against the weight of the drill rig. These samples are said

FIGURE 8.21 Sequential steps for the collection of a core sample through a hollow-stem auger.



Source: G. Hackett. 1987. Drilling and constructing monitoring wells with hollow-stem augers part 1: Drilling considerations. *Groundwater Monitoring & Remediation* 7:51–62. Used with permission.

to be *undisturbed*, although they are in fact minimally disturbed. The precise method of collecting a Shelby tube sample is described in method ASTM D1587 (American Society for Testing and Materials 1983). The sample can be extruded from the Shelby tube in the lab and trimmed into a permeameter for a permeability test. Details of the microstratigraphy can be examined as well. Shelby tube sampling does not work with noncohesive sediments.

A **split-spoon sampler** can be used for the collection of samples of both cohesive and noncohesive sediments. The split-spoon sampler consists of a split tube with thicker walls than a Shelby tube. The two halves are placed together and joined by screwing a circular drive shoe on the bottom and a head assembly on the top. The assembled split-spoon sampler is screwed to a rod and lowered to the bottom of the drill hole. A pipe-like weight of 63.5 kg (140 lb) is placed on the top of the rod.

The weight is repeatedly raised and dropped a distance of 76 cm (30 in.) in order to drive the split-spoon sampler into the formation. The number of blows necessary to drive the sampler every 15cm (6 in.) is recorded as the sampler is driven 46 cm (18 in.) into the formation. The more dense the formation, the greater the number of blows needed to drive it 15 cm (6 in.). The process is described by ASTM 1586 (American Society for Testing and Materials 1984).

After the split-spoon sampler is driven 46 cm (18 in.), or after refusal, it is brought to the surface and opened. Frequently, less than 46 cm (18 in.) of sediment have been collected. Fine, noncohesive sediment such as sand may fall out of the sampler as it is being retrieved. Sediment greater in diameter than one-third of the diameter of the sampler may not enter it at all. A pebble may lodge in the barrel and not allow any other sediment to enter. Sediments may compact in the sampler so that a full 18-inch sample may actually occupy less than 46 cm (18 in.) of the core barrel. The hydrogeologist examining the split-spoon sample must use his or her judgment in making a log based on the split-spoon samples. Figure 8.22 is a photograph of a split-spoon sample.

FIGURE 8.22 Hydrogeologist describing a split-spoon sample.

Photo credit: C.W. Fetter.

A standard for core samples is to collect one 46 cm (18 in.) sample every 1.5 m (5 ft). This frequency of sampling is suitable for relatively homogeneous formations. However, if the microstratigraphy of the formations is important—for example, if there are permeable sand seams in a clay formation—then continuous-core samples should be collected. Continuous cores are made by advancing the drill bit to the full depth that was sampled by a split spoon and then immediately taking another core sample of the fresh formation ahead of the previous core. Continuous-core samples can also be collected in cohesive soils by using a special core barrel that collects a 1.5 m (5 ft) long sample inside a hollow-stem auger as the auger is being advanced. If a sequence consisting of a 3-inch split spoon followed by a 6.35 cm (2.5 in.) split spoon followed by a 5 cm (2 in.) split spoon is used, 1.37 to 1.5 m (4.5 to 5 ft) of continuous sample core can be collected before the augers need to be advanced.

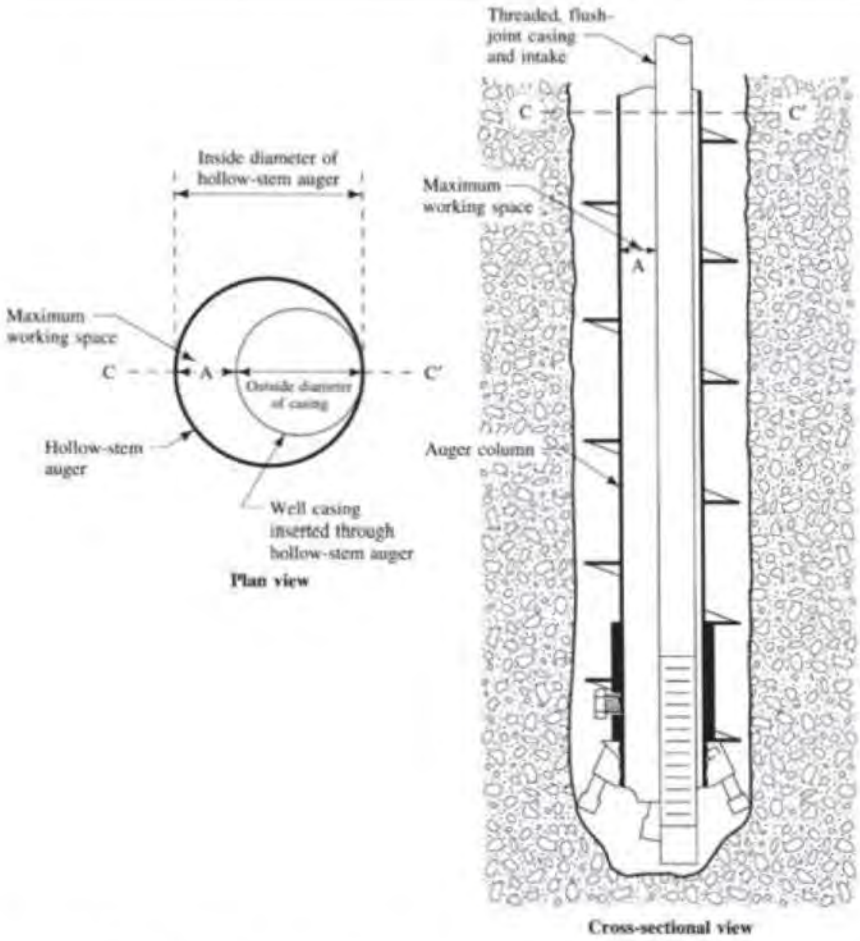
In consolidated formation a rock-core sample is collected by use of a core barrel with a diamond-studded bit. The rotating bit grinds up rock in an annular pattern, leaving an undisturbed center of rock that enters the core barrel. There is a core lifter just behind the bit to keep the core from falling out of the core barrel when the drill rods and bit are retrieved from the borehole. For shallow soil sampling, some coring and auger soil sampling devices can be operated by hand. Helical or post-hole augers gather a disturbed, near-surface sample and are superior to coring devices in rocky soils. Soil cores can be taken by hand from the ground surface with specialized coring devices that can allow sampling for VOCs and other potential contaminants. Cores are typically extruded after sampling and readied for transport or analysis. Decontamination techniques for coring equipment between samples is required to prevent cross-contamination.

8.5.5 Installation of Monitoring Wells

Following the collection of samples during the installation of borings, a monitoring well can be installed in the borehole. Boreholes drilled with mud should stay open with the drill rod removed. Hollow-stem augers are generally left in the ground and the well is installed through them, as is drive casing in cable-tool drilling. There must be a sufficient working opening inside the casing or augers. For a 5 cm (2 in.) nominal monitoring well, this means a minimum 10.8 cm (4.25 in.) opening is needed. The casing can be offset within the auger to give the largest working opening (Figure 8.23) although care must be taken to keep the well casing and screen as centrally located as possible. With a 10.8 cm (4.25 in.) inside diameter auger and a 5 cm (2 in.) nominal casing, this creates a 4.76 cm (1.875 in.) working opening.

The first step in the installation of a monitoring well is to screw the well screen to the casing and then lower the assembly through the inside of the augers or temporary casing. Prior to installation the casing and screen should be thoroughly decontaminated. The casing and screen may be wrapped in white butcher paper after it has been decontaminated and then kept wrapped until just before it is lowered into the augers. Figure 8.24 shows a 6.1 m (20 ft) casing and screen being lowered by hand. Longer casings need to be lowered on a cable using the drilling rig. In boreholes not drilled by hollow-stem augering, it is generally important to have centralizers (mechanical collars-type devices) attached to the casing/ screen combination to keep them from contacting the wellbore walls (Nielsen 2005).

FIGURE 8.23 Casing offset inside hollow-stem auger to give greatest working opening.



Source: G. Hackett. 1988. Drilling and constructing monitoring wells with hollow-stem augers part 2: Monitoring well installation. *Groundwater Monitoring & Remediation* 8:60–68. Used with permission.

Once the casing and screen have been lowered into the well, the filter-pack material needs to be placed. The volume of filter-pack material necessary to fill the annular space between the screen and casing and the borehole wall from the bottom of the borehole to a point 0.6 m (2 ft) above the top of the screen should be computed. At least this much material must be on hand before starting the filter-pack installation. A weighted measuring tape is lowered into the working opening between the casing and the hollow-stem auger and the total depth of the borehole is measured and recorded.

If the formation is cohesive and can stand open for a short while, the augers are withdrawn 0.3 or 0.6 m (1 or 2 ft) from the bottom. Filter-pack material is then poured into the working opening, and the annular space is filled to the level of the auger bit. Care should be taken that the filter-pack sand doesn't fill the space between the casing and the augers, because it can lock the casing and hollow-stem augers together. The weighted tape is used to determine the position of the top of the filter pack. The augers are then withdrawn another 0.3 to 0.6 m (1 to 2 ft), and the process is repeated until the entire filter pack is placed. Figure 8.25 illustrates what is known as the free-fall method of filter-pack emplacement.

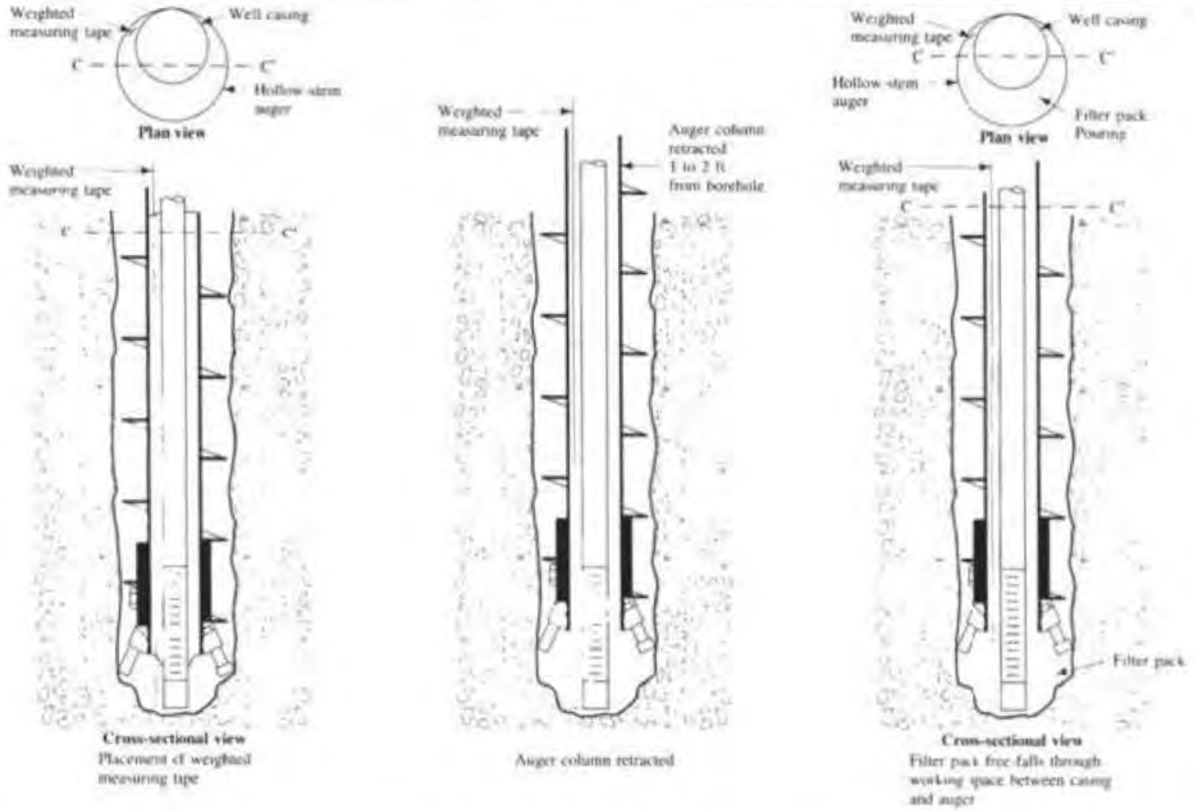
FIGURE 8.24 Lowering well screen and casing into hollow-stem augers. Note the white wrapping paper around the decontaminated casing.

Photo credit: C. W. Fetter.

When filter-pack material drops through a water column, it may separate according to size. It may also bridge the space between the casing and the auger and create a void below. To avoid these problems, a **tremmie pipe** should be used wherever possible (Figure 8.26). A tremmie pipe is a pipe that extends from the surface and through which the filter-pack sand may be poured. After the augers are withdrawn a few feet, the annular space is filled with sand being poured down the tremmie pipe. The tremmie pipe is raised as the level of sand rises. The tremmie pipe can be used to tamp down the sand, and the weighted tape is used to measure the position of the top of the filter pack.

If the formation is noncohesive, it will collapse as the augers are withdrawn. Under these conditions, the withdrawal of the augers and the addition of the filterpack

FIGURE 8.25 Free-fall method of filter-pack emplacement with a hollow-stem auger. The method also works with drive casing.



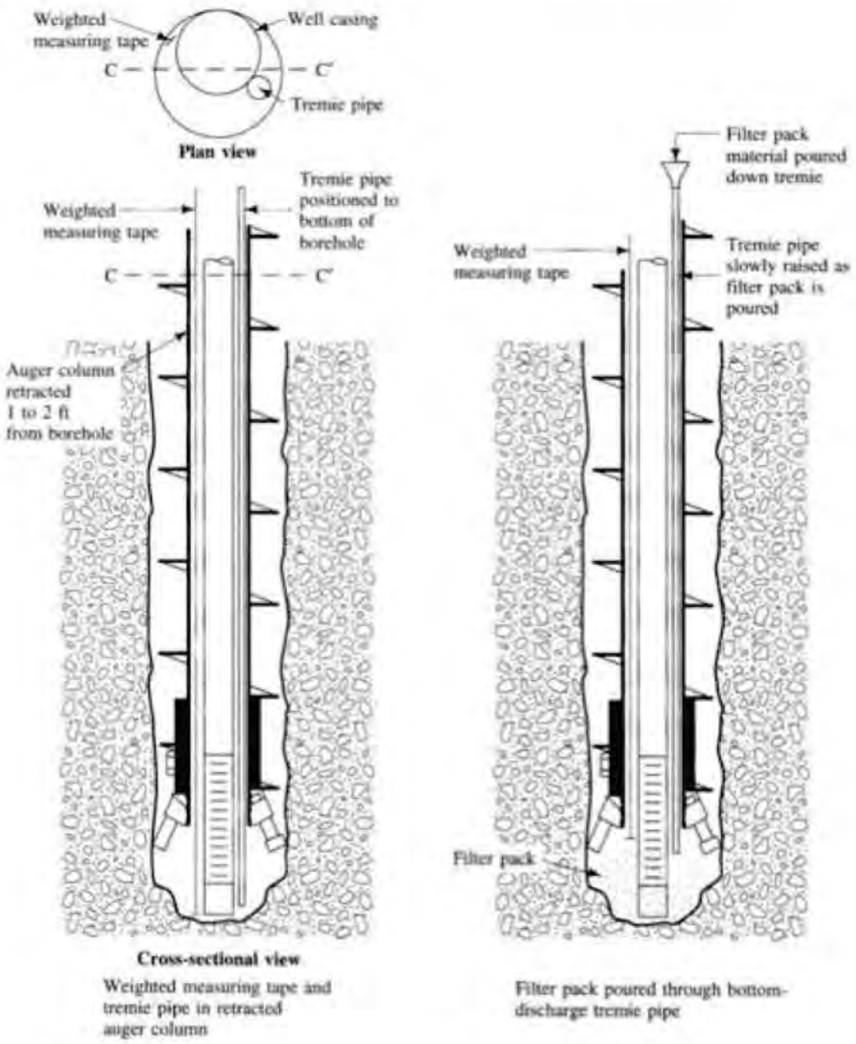
Source: G. Hackett. 1988. Drilling and constructing monitoring wells with hollow-stem augers part 2: Monitoring well installation. *Groundwater Monitoring & Remediation* 8:60–68. Used with permission.

material must occur simultaneously (Hackett 1988). A cable must be attached to the top of the auger string so that the working opening is accessible at all times. The hollow stem of the augers is filled with clean water, and a positive hydraulic head is thus maintained throughout the operation. The augers are very slowly withdrawn, and at the same time filter-pack material is added so that the top of the filter pack is within an inch or so of the bottom of the augers. This requires precise coordination of the rate of addition of filter-pack sand and the rate of withdrawal of the augers.

The final depth of the top of the filter pack is confirmed by measurement with the weighted tape. It should be 0.6 m (2 ft) above the top of the screen. The augers are then withdrawn another 0.6 m (2 ft) and 0.6 m (2 ft) of pure bentonite clay is placed by free fall through the working space. If the area is below the water table, bentonite pellets are used; if the area is above the water table, granular bentonite or slurry is used (see 8.4.5). Pellets should be dropped a few at a time so that they aren't caught in the working space as they start to swell by hydration. The weighted tape is used to confirm the final thickness of the bentonite layer after enough time has elapsed to allow the bentonite to hydrate. Bentonite pellets should not be used as grout in the vadose zone, as hydration is extremely slow even if water is poured through the pellets.

Placement of the annular seal should take place by use of a tremmie pipe. The tremmie pipe should be lowered to the top of the bentonite seal. The augers are

FIGURE 8.26 Use of a tremmie pipe for emplacement of filter-pack material.

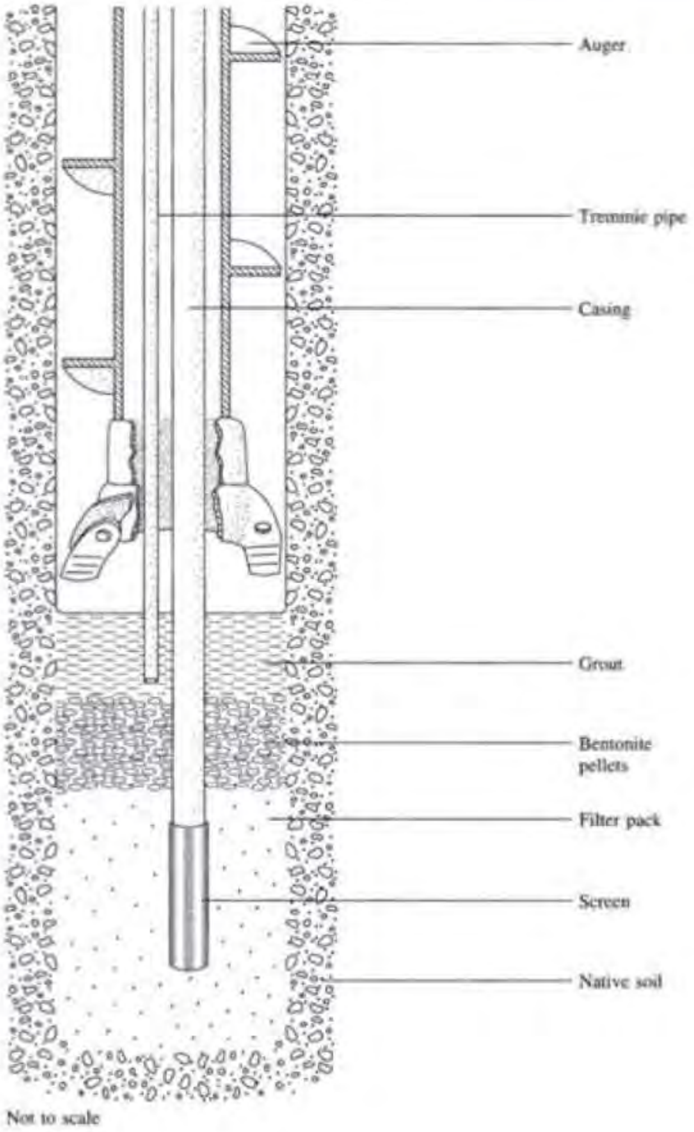


Source: G. Hackett. 1988. Drilling and constructing monitoring wells with hollow-stem augers part 2: Monitoring well installation. *Groundwater Monitoring & Remediation* 8:60–68. Used with permission.

withdrawn 0.6 m (2 ft) or so and the annular space is filled from the bottom with grout, which is either pumped down the tremmie pipe or is fed by gravity (Figure 8.27). The weighted tape is used to confirm the position of the top of the grout. The augers are then repeatedly withdrawn and grout is emplaced until it is brought close to the surface. The tremmie pipe can be left at the bottom until the grout is brought to the surface, or it can be raised as the augers are withdrawn. For slumping sediments, the grout must be emplaced simultaneously and at the same rate as the augers are withdrawn.

The final step is the installation of a locking protective cap. Bentonite-cement can be brought all the way to the surface. If bentonite grout or bentonite-sand grout is used, the final few feet filling the annular space must be neat cement or bentonite-cement grout. A slight mounding of the surface grout will prevent the pooling of water at the surface next to the well. The locking protective casing can be pushed into the cement grout when

FIGURE 8.27 Use of a tremmie pipe for emplacement of grout above the bentonite pellets.



it is still soft. If the grout settles overnight, its level should be brought to the surface with additional material. A stronger surface seal can be obtained if the top 0.61 m (2 ft) of the annular space is filled with concrete, as opposed to bentonite-cement grout.

8.5.6 Monitoring Well Development

Once a monitoring well is constructed, it is necessary that it undergo development. This is a process of removing fine sand, silt, and clay from the aquifer around the well screen. If drilling mud was used, then vigorous development may be needed to break down the mud pack on the borehole wall. Development is needed to create a well that ideally will not pump silt and clay when it is sampled. It also may create a zone around the well screen that is more permeable than the native soil and that stabilizes the native soil so that the fine sediments do not enter the filter pack.

Aller et al. (1991) made the following observations about monitoring well development:

1. Using compressed air for well development may alter native water chemistry, crack the casing, or blow the bottom cap off the screen.
2. Adding water to the well for flushing the well or surging can alter the groundwater chemistry, at a minimum by dilution.
3. Breaking down a mud wall left in the borehole from mud-rotary drilling is very difficult.
4. Developing a well when the screen is in a clean, homogeneous, high-permeability aquifer is relatively easy.
5. Developing a well when the screen is in a fine-grained, stratified, low-permeability formation is difficult.
6. Developing a large-diameter well is easier than developing a small-diameter well.
7. Shallow monitoring wells are easier to develop than deeper monitoring wells.
8. Monitoring wells that can be bailed dry tend to be turbid because of the steep hydraulic gradients that are developed.
9. In the final analysis, many monitoring wells cannot be developed to the point where a nonturbid, groundwater sample can be collected. This is especially true if the formation does not yield very much water, so that extensive development is not possible.

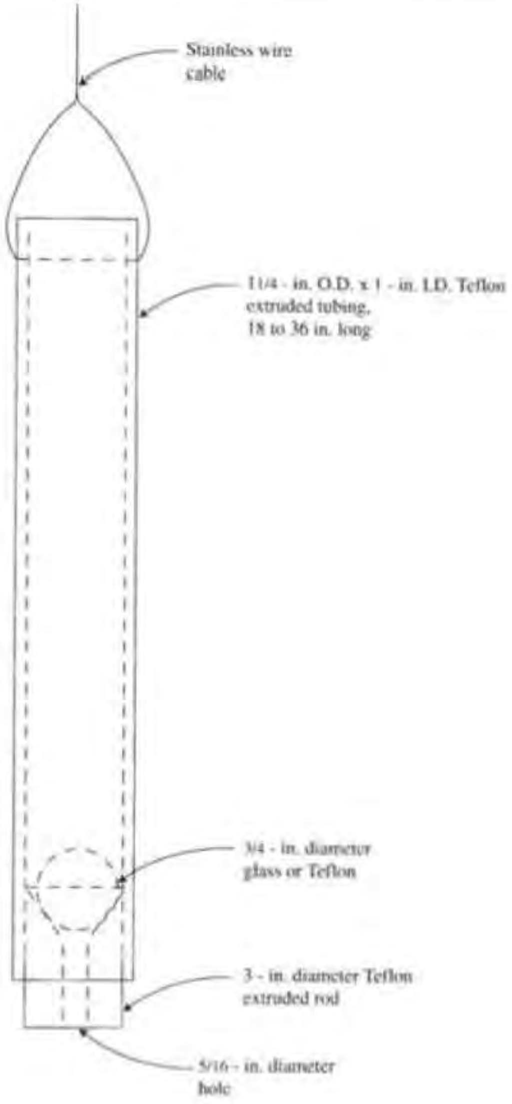
If the borehole is drilled into a stable, consolidated formation, especially if mud is used during the drilling, it may be advantageous to flush the borehole with potable, fresh water to wash out as much of the mud as possible prior to installation of the well and filter pack. This will greatly cut the time needed for well development. In some cases it will not be permissible to add water to the borehole, since this might alter the groundwater chemistry.

There are three procedures used for monitoring well development: bailing, surge block surging, and pumping/overpumping/backwashing. These may be used alone or in combination.

A **bailer** for a monitoring well is a section of pipe that is open on the top end and has a foot valve on the bottom end. It is attached to a line so that it can be lowered into the well. Water fills it from the bottom; then when it is raised by the line, the foot valve closes and the water inside is trapped. Figure 8.28 is a diagram of a bailer.

When developing a well by bailing, the bailer should be allowed to freefall to the water surface. When it strikes the water, a pressure wave results, which pushes water from the well screen out into the formation. After the bailer is filled with water, it is withdrawn and water from the formation enters the screen. This back-and-forth motion of water through the filter pack loosens fine sediment so that it can be drawn into the well and removed by the bailer. The bailer should be allowed to sink to the screen area so that the water that fills it contains the fine sediment that is brought into the well from the filter pack. The bailer can also be raised and lowered when it is submerged to force water to move back and forth through the screen area. Bailing can take some hours to develop a monitoring well effectively; this can translate into significant labor cost. Bailing for development can be undertaken by hand or by using a cable attached to a

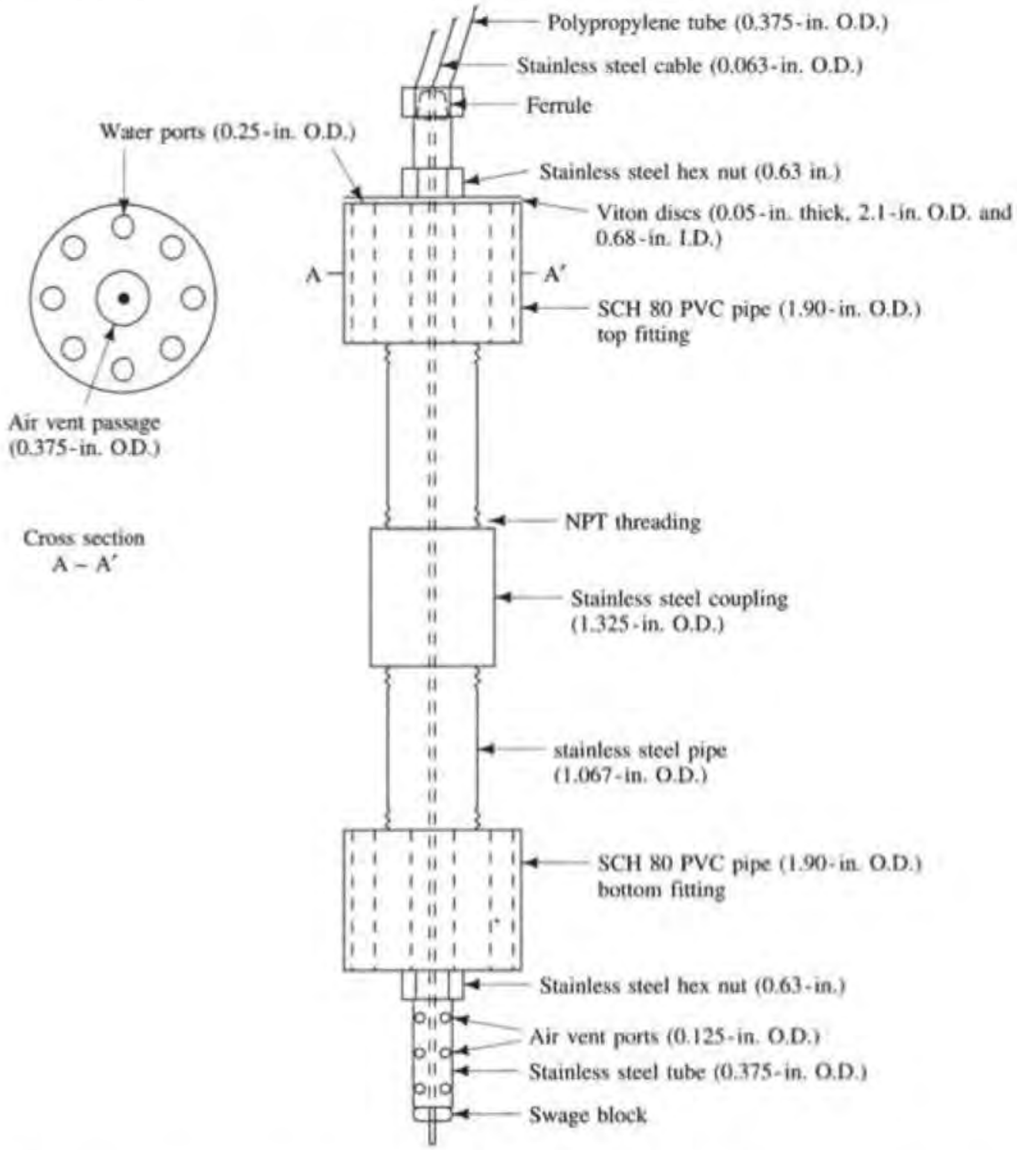
FIGURE 8.28 Diagram of a bottom-loading bailer.



power-operated drum on a drill rig or truck. Some well-development outfits have an arm that can go up and down like a walking beam to create a surging action. Care should be taken so that the surging action is not vigorous enough to collapse the well screen.

A **surge block** is a device that fits inside the well with a flexible gasket that is close in size to the inside diameter of the well. Figure 8.29 shows the design of a surge block for small-diameter monitoring wells. It is attached to a rod that is raised and lowered with a stroke of about 0.9 m (3 ft). Most of the water is moved up or down by the action of the surge block, although some fraction of the water bypasses the surge block. The surging is initiated with the surge block at the top of the well screen, and the block is gradually lowered until the entire screened area has been surged. Every so often the surge block is removed and the well bailed to remove the sediment that has been brought into the well. If too much sediment accumulates above the surge block, it can bind between the surge block and the casing wall and lock up the surge block. To avoid this, the surge block

FIGURE 8.29 Design of a specialized surge block for monitoring wells.



Source: R. Schalla and R. W. Landick. 1986. A new valved and air-vented surge plunger for developing small-diameter monitor wells. *Groundwater Monitoring & Remediation* 6:77–80. Used with permission.

must be removed and the well bailed frequently. Surging begins with a gentle action; as development progresses it becomes more vigorous, with a more rapid plunging action. Again, too vigorous a surging action might cause the screen to collapse.

Pumping the well can aid in development. A number of different types of pumps are suitable. However, some pumps might be damaged by the sediment that must necessarily be removed during development. The ideal pump for development is capable of a wide range of flow velocities and does not have a valve that prevents backflow. The pump intake should be in the screen zone so that it will immediately pick up sediment that is brought into the well. The pump is started at a low velocity and is shut off every so often. When it is shut down, the water in the pump column between the water surface and the pump will flow back into the well and out into the filter pack. When the pump is started again, this water will be drawn into the well and will loosen fine sediment in the filter pack. With time, the rate at which the well is pumped is increased so that the water velocity through the filter pack into the screen is increased. Eventually, the well will be overpumped—that is, pumped at a rate that is greater than the flow into the well through the well screen. There will be a rapid decrease in the water level in the well during overpumping, and it cannot be sustained for very long. Eventually the water from the well should clear. Monitoring wells should be periodically redeveloped.

8.5.7 Record Keeping During Monitoring Well Construction

Many localities have detailed record-keeping requirements for monitoring well construction. Even when detailed records aren't required by statute, they should be kept as a matter of sound professional practice. Figure 8.30 shows a one-page form that can be used to record important information on monitoring well construction. Many firms have their own forms, and many states, provinces, and regions have a required form. The form should be filled out in the field as the information is collected.

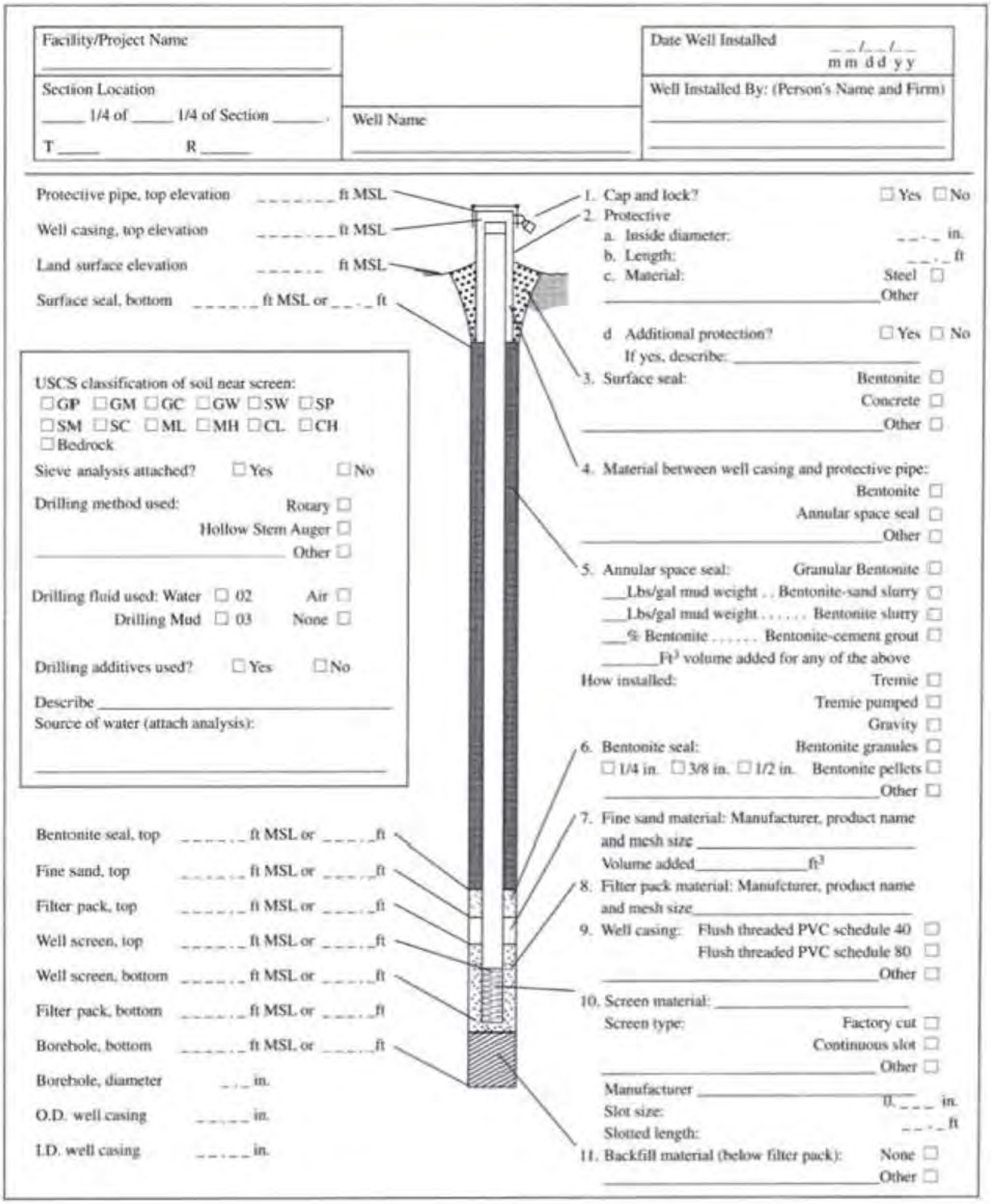
Records should also be kept of well development, including the date that it occurred, the method used, the water level at the start of development, the water level at the end of development, the time spent developing the well, and the volume of water removed. The thickness of sediment on the bottom of the well can be determined by measuring the depth to the bottom of the well with a weighted tape. This measured distance is subtracted from the measured length of the well casing and screen that was installed. The difference between the two dimensions is the thickness of sediment inside the well. This thickness should be measured and recorded both before and after development. If possible, sediment should be removed with a bottom-loading bailer.

8.5.8 Monitoring Well and Borehole Abandonment

Sometimes difficulties are encountered during the construction of a monitoring well that prevent its completion. Monitoring wells may be installed for a specific time period, after which they must be removed. Test borings may be made with no intention of using the borehole for construction of a monitoring well. In all such cases, proper abandonment of the well should be undertaken. Many countries and regions have specific well-abandonment codes. In the absence of specific requirements, monitoring wells and boreholes should be abandoned in such a manner that surface water cannot drain into the aquifer. Otherwise a direct connection for contaminated water from the surface to the aquifer can result. Nor should contaminated water or fluids be allowed to move vertically within the borehole to contaminate other depths.

If a casing and screen have been installed, they should be removed if possible. This can be accomplished by pulling if the annular seal has not been filled with a cement-type grout. If a plastic casing breaks while being pulled, it can be removed by drilling it out with hollow-stem augers. Following the removal of the casing, a tremmie pipe should be used to fill the resulting borehole from the bottom with an appropriate material, such as neat cement or bentonite grout. The grout is placed while the augers are being pulled out of the hole. Material removed from a monitoring well may be contaminated and should be properly disposed of.

FIGURE 8.30 Form for recording information about construction details of a monitoring well.



Facility/Project Name ______

Section Location
____ 1/4 of ____ 1/4 of Section ____.
T ____ R ____

Well Name ______

Date Well Installed __/__/__ mm dd yy

Well Installed By: (Person's Name and Firm) ______

Protective pipe, top elevation ______ ft MSL

Well casing, top elevation ______ ft MSL

Land surface elevation ______ ft MSL

Surface seal, bottom ______ ft MSL or ____ ft

USCS classification of soil near screen:
☐ GP ☐ GM ☐ GC ☐ GW ☐ SW ☐ SP
☐ SM ☐ SC ☐ ML ☐ MH ☐ CL ☐ CH
☐ Bedrock

Sieve analysis attached? ☐ Yes ☐ No

Drilling method used: Rotary ☐
Hollow Stem Auger ☐
______ Other ☐

Drilling fluid used: Water ☐ 02 Air ☐
Drilling Mud ☐ 03 None ☐

Drilling additives used? ☐ Yes ☐ No

Describe ______
Source of water (attach analysis): ______

Bentonite seal, top ______ ft MSL or ____ ft

Fine sand, top ______ ft MSL or ____ ft

Filter pack, top ______ ft MSL or ____ ft

Well screen, top ______ ft MSL or ____ ft

Well screen, bottom ______ ft MSL or ____ ft

Filter pack, bottom ______ ft MSL or ____ ft

Borehole, bottom ______ ft MSL or ____ ft

Borehole, diameter ____ in.

O.D. well casing ____ in.

I.D. well casing ____ in.

1. Cap and lock? ☐ Yes ☐ No
2. Protective
   a. Inside diameter: ____ in.
   b. Length: ____ ft
   c. Material: Steel ☐
   ______ Other
   d Additional protection? ☐ Yes ☐ No
   If yes, describe: ______
3. Surface seal: Bentonite ☐
   Concrete ☐
   ______ Other ☐
4. Material between well casing and protective pipe:
   Bentonite ☐
   Annular space seal ☐
   ______ Other ☐
5. Annular space seal: Granular Bentonite ☐
   ___ Lbs/gal mud weight . . Bentonite-sand slurry ☐
   ___ Lbs/gal mud weight . . . . . . Bentonite slurry ☐
   ___ % Bentonite . . . . . . Bentonite-cement grout ☐
   ______ Ft³ volume added for any of the above
   How installed: Tremie ☐
   Tremie pumped ☐
   Gravity ☐
6. Bentonite seal: Bentonite granules ☐
   ☐ 1/4 in. ☐ 3/8 in. ☐ 1/2 in. Bentonite pellets ☐
   ______ Other ☐
7. Fine sand material: Manufacturer, product name and mesh size ______
   Volume added ______ ft³
8. Filter pack material: Manufcturer, product name and mesh size ______
9. Well casing: Flush threaded PVC schedule 40 ☐
   Flush threaded PVC schedule 80 ☐
   ______ Other ☐
10. Screen material: ______
    Screen type: Factory cut ☐
    Continuous slot ☐
    ______ Other ☐
    Manufacturer ______
    Slot size: 0.___ in.
    Slotted length: ____ ft
11. Backfill material (below filter pack): None ☐
    ______ Other ☐

Source: Modified from Wisconsin Department of Natural Resources.

If the casing and screen have been grouted into place, it may not be possible to remove them. If this is the case, several approaches can be used. The casing could be cut off below grade; then the screen and casing must be filled from the bottom using a tremmie pipe and an appropriate material such as neat cement or bentonite grout. If the casing is in poor condition it can be ripped or perforated with casing rippers allowing grout to be injected into the annular space. Alternatively, casing can be gun-perforated using either a device that fires steel projectiles through the casing and into the formation, or a jet type perforator that uses small shaped explosive charges to burn holes through the casing and allow grout injection (Aller et al. 1991).

Boreholes in sediments can be filled with grout or native soils mixed with bentonite. Boreholes into bedrock should be grouted with a cement-type grout.

8.6 Well Sampling

8.6.1 Introduction

After a monitoring well has been designed, installed, and developed, the next step is to collect a water sample. The water sample should be representative of the water in the formation; that is, the sampling techniques should collect water from the aquifer and not from water that has been standing in the well casing or screen. In addition, the sampling device should provide a sample that has not been altered by the sampling process and should not cause cross contamination.

8.6.2 Fluid Level and Pressure Measurement

Several devices are available for the downhole measurement of water levels, pore pressures and NAPL layers in wells or piezometers. Historically, steel tape was used to measure water levels in wells. Chalk would be applied to the tape at the expected water level depth, and then retrieved to the surface. The depth to water would be indicated on depth markings on the tape at the point where the chalk had been washed away by the water. Another historical method to measure hydraulic head is a "bubble tube" which is a pipe or tube sent downhole with a known air pressure to depths below land surface and below the water table or piezometric surface. The tube continues to bubble until it reaches a depth where the water pressure is equal to the air pressure within the tube and the depth below water surface can be calculated. This method is not used in situation where volatilization of contaminants is possible or LNAPLs are suspected in the wells.

Water levels are now often determined by electrical probes with depth demarcations which are lowered in a well or piezometer until a peeping sound indicates that the water level has been reached. For more exacting and quantitative NAPL determinations in wells, depth-discrete and transparent bailers can be sent downhole, or interface probes can be used. An interface probe is a modified electrical water level probe which has an ability to give separate acoustic and visual signals for water and NAPL in the fluid column (Mercer and Cohen 1990; Cohen and Mercer 1993). Unlike the bailer, however, interface probes cannot retrieve a NAPL sample for analysis, but only measure the vertical thickness of NAPL in a well.

Long term water level measurements are now often made with a recording transducer which measures temporal pressure changes in a well at a specified depth, which correlates to overlying water levels. Vibrating wire piezometers are useful in measuring well water levels and pore pressures for geotechnical applications.

8.6.3 Well Purging

Water that has been standing in the well has been in contact with atmospheric gases and the well casing and screen. This contact can affect the water chemistry. Oxygen can diffuse into the water and dissolved gases can volatilize or oxidize. Trace elements may be leached from the well casing. Organics may be sorbed by the well casing. In order to be sure that the water being drawn into the sampling device comes from the aquifer, the well must be purged of standing water prior to sampling. The goal of purging is to remove all the water that has been standing in the well. The volume of water that must be removed to accomplish that goal depends upon the method of purging and formation permeability.

The first step in well purging is to measure the depth of water in the well, the total well depth, and the inside diameter of the well casing. These measurements are used to compute the volume of water standing in the casing. If a well is purged by a method that withdraws water from the top of the water column, then theoretically only one well volume needs to be withdrawn. For example, purging with a bailer that is lowered slowly into the well to a depth no greater than the length of the bailer will remove water only from the top of the column. If a pump is used to purge the well, the pump intake should be as close as possible to the top of the water column. Although one well volume would theoretically remove all the standing water, good practice suggests that at least three well volumes should be removed to be sure that the standing water in the casing and screen is totally removed. This also removes water from the filter-pack area. If a well is bailed dry, or nearly so, it is not necessary to attempt to remove multiple-well volumes. As soon as the well has recovered enough to contain sufficient sample volume, the sample can be collected.

If the pump intake is lowered to the level of the screen in the well during purging, then most of the water will come from the screen area, and an area of stagnant water will develop in the water column above the pump intake. Under such conditions up to five well volumes need to be pumped to remove all of the stagnant water in the well (Gibb et al. 1981). Keeley and Boateng (1987) advocate a staged technique when purging with a pump. The pump intake is lowered to just below the water surface at the beginning of the purging process and then is gradually lowered through the water column until it is at the screen zone, when purging is complete. Purging three well volumes with this technique should be adequate.

Electrical conductivity and pH can be monitored during the well-development procedure. If they vary widely during the well-purging process, this may mean that water from different sources is being withdrawn. If these values do not stabilize, this does not necessarily mean that the stagnant water has not been withdrawn from the well. There may be instrument drift, or the water quality in the aquifer may be changing as water from different parts of the aquifer is being withdrawn. If possible, the well should be purged until it is not turbid.

The water being purged from the monitoring well may be contaminated. If so, it must be properly disposed of in a treatment facility. For this reason, purging techniques that limit the amount of water withdrawn are desirable.

8.6.4 Well-Sampling Devices

There are a large number of sampling devices available for monitoring wells. They operate under different physical principles and designs and have different applications.

Most are available in a variety of materials. The following is a partial list of available devices (Nielsen and Yeates 1985; Pohlmann and Hess 1988):

1. *Open bailer*: This device is a rigid tube with an open top and either a closed bottom or a check valve on the bottom. It is attached to a line and is lowered and raised by hand. It withdraws the sample from the top of the water column.
2. *Point-source bailer*: This device has a check valve on both the top and bottom and can be lowered on a line to a given depth below the surface, where the valves can be closed by a cable. It can collect grab samples from any depth in the water column. Some bailers are intentionally disposable to prevent cross-contamination from multiple sampling, and some are transparent or translucent allowing visual identification of colored NAPLs or other compounds in the bailer.
3. *Syringe sampler*: A medical syringe, or similar device, is attached to a length of tubing and is lowered to a selected depth in the water column. A suction is applied to the tubing and the syringe, which was lowered in the "empty" position. The syringe fills as the water comes into the needle because of the vacuum being developed by the suction on the tubing.
4. *Gear-drive pump*: This device is similar to a traditional submersible electrical pump. There is a miniature electrical motor attached to the pump, which rotates a set of gears to drive the sample up the discharge line via positive displacement. A continuous flow of water under positive pressure is developed.
5. *Bladder pump*: This sampler has a rigid tube containing an internal flexible bladder. There are check valves on either end of the rigid tube. When the bladder is deflated, water enters the lower end of the tube through the check valve. When the tube is full, the bladder is inflated with an inert gas pumped down from the surface. The bottom check valve closes, the top check valve opens, and the water sample flows up the discharge line. When the bladder deflates, the water in the discharge line can't drain back into the rigid tube because of the check valve. The water is under positive pressure at all times and doesn't come into contact with the gas.
6. *Helical-rotor pump*: This pump has a submersible electrical motor. It rotates a helical rotor-stator, which drives water up the discharge line under positive pressure.
7. *Gas-drive piston pump*: A piston that pumps the water is driven up and down by gas pressure from the surface. The gas does not contact the sample.
8. *Submersible centrifugal pump*: A submersible electrical motor drives an impeller in the pump, which creates a pressure and forces the water up a discharge line.
9. *Peristaltic pump*: Unlike the others, this is a pump located at the land surface. It is a self-priming vacuum pump that can draw a water sample up tubing under suction. Loss of volatile compounds and dissolved gases may occur due to the vacuum developed.
10. *Gas-lift pump*: A constant stream of gas or air is used to force the water up a discharge tube. The water comes into contact with the gas or air and oxidation and loss of volatiles can occur.
11. *Gas-driven pump*: An inert gas is used to alternately pressurize and depressurize a sample chamber. The sample chamber has check valves to create a one-way flow

of water up a discharge line. This is similar to a bladder pump except that there is no bladder, so the gas comes into contact with the water sample.

12. *Passive samplers*: Consist of an organic phase, such as a plastic film or polymer, which accumulates contaminants from the aqueous phase or (soil) air. Passive samplers are useful for sampling the water column as well as interstitial water (ITRC 2005; USEPA 2012).

Figure 8.31 is a matrix of sampling devices and the suitable applications for collection of groundwater samples.

Pearsall and Eckhardt (1987), Yeskis et al. (1988), and Tai, Turner, and Garcia (1991) evaluated the efficacy of a number of different sampling devices in collecting representative samples of volatile organic compounds in groundwater. The first two studies were performed by withdrawing water from monitoring wells with different devices and comparing the results. The authors had no controls—that is, they did not know the actual concentration of the contaminants in the aquifer.

Yeskis et al. (1988) tested a bailer, a bladder pump, a piston pump, a submersible electric impeller pump, and a submersible electric helical stator-rotor pump. They found very little variation in the results except for the bailer. The bailer samples were in general less than half of the values obtained by the other devices. Pearsall and Eckhardt (1987) evaluated two 5 cm (2 in.) submersible helical stator-rotor pumps made of different materials, a 4-inch submersible electrical water-well pump, a cast-iron centrifugal suction pump, a peristaltic pump, and a bailer. The submersible pumps all gave similar results; the peristaltic and centrifugal suction pumps gave somewhat lower results. Silicon and PVC tubing appeared to give lower results than Teflon® tubing when used with the same pump. The bailer gave variable results, depending upon the concentration.

Tai, Turner, and Garcia (1991) built a 30.5 m (100 ft) tall, 12.7 cm (5 in.)-diameter, stainless-steel, vertical standpipe with sampling ports at various depths. They were able to use a sampling device to collect a sample from the standpipe, at the same time drawing a control sample from that depth through a sample port. They tested a Teflon® point-source bailer, a manual-driven piston pump, a motor-driven piston pump, a submersible helical-rotor pump, a peristaltic pump, and a bladder pump. Teflon® tubing was used to convey samples to the surface from the pumps. Because they had control samples, they were able to calculate a percent recovery for each sampling device. Table 8.5 shows the percent recovery for each sampling device at different depths. Examination of this table shows that the submersible pump, the peristaltic pump, and the bladder pump all had excellent recoveries, ranging from 98.5 to 100.5%. The other three devices were not as accurate, with the bailer having the lowest recovery.

The low recovery using the bailer was probably due to agitation of the sample as it was being transferred from the bailer to a 40 mL sample bottle for volatile organic analysis. Although it is a simple piece of equipment, an experienced operator is needed for correct use of a bailer.

On the basis of available research (Parker 1994) the piston pump, the bladder pump, and the electrical submersible helical-rotor pump appear to be the best devices for the collection of water samples containing volatile organic compounds. Peristaltic pumps are also suitable for metals and semivolatile organics if used with a rheostat to

FIGURE 8.31 Matrix showing applications of a number of groundwater sampling devices.

						Ground Water Parameters													
						Inorganic							Organic				Radioactive		Biol.
		Device	Approximate Maximum Sample Depth	Minimum Well Diameter	Sample Delivery Rate or Volume	EC	pH	Redox	Major Ions	Trace metals	Nitrate, Fluoride	Dissolved Gases	Non-volatile	Volatile	TOC	TOX	Radium	Gross Alpha & Beta	Coliform Bacteria
Portable Sampling Devices	Grab	Open bailer	no limit	½ in.	Variable	•			•	•	•		•				•		•
		Point-source bailer	no limit	½ in.	Variable	•	•	•	•	•	•		•	•	•	•	•		•
		Syringe sampler	no limit	1½ in.	0.01–0.2 gal	•	•	•	•	•	•		•				•	•	•
	Positive displacement (submersible)	Gear-drive	200 ft	2 in.	0–0.5 g/min									•					
		Bladder pump	400 ft	1½ in.	0–2 g/min	•	•	•	•	•	•	•	•	•	•	•	•	•	•
		Helical rotor	160 ft	2 in.	0–1.2 g/min	•	•	•	•	•	•	•	•	•	•	•	•	•	
		Piston pump (gas-drive)	500 ft	1½ in.	0–0.5 g/min	•			•	•	•		•				•	•	
		Centrifugal	variable	3 in.	variable	•			•		•						•	•	
	Suction lift	Peristaltic	26 ft	½ in.	0.01–0.3 g/min	•			•		•		•				•		•
	Gas contact	Gas-lift	variable	1 in.	Variable														
		Gas-drive	150 ft	1 in.	0.2 g/min	•			•		•		•				•		

Source: K. F. Pohlmann and J. W. Hess. 1988. Generalized ground water sampling device matrix. *Groundwater Monitoring & Remediation* 8:82–84. Used with permission.

TABLE 8.5 Percent recovery of sampling devices compared with control samples.

	Water Depth					
	17.5 ft		54 ft		92 ft	
Sampler	Low[a] Conc.	High[b] Conc.	Low[a] Conc.	High[b] Conc.	Low[a] Conc.	High[b] Conc.
Submersible pump	97.8	99.7	99.5	98.5	100.1	100.1
Peristaltic pump	97.7	98.7	98.7	98.5	97.7	100.0
Bladder pump		101.5		100.5		99.9
Teflon bailer	93.9	96.3	92.4	93.9	92.7	91.4
Manual-driven piston pump	102.2	—	102.5	101.1	102.3	103.5
Motor-driven piston pump	97.4	96.8	99.8	98.4	100.9	100.7

Source: Tai et al. 1991.

create a low pumping rate. A bailer is acceptable if used properly with a minimum of agitation so as not to create splashing in the well and loss of volatiles. Bailers should have a bottom-emptying device. Such a bailer should be able to recover 90% of the volatile organics in the water.

Parker and Ranney (1996) examined the effect on using various rigid and flexible tubing used in water sampling devices on trace-level dissolved-organic compounds present in groundwater. They found that fluorinated ethylene propylene (FEP), FEP-lined polypropylene and polyvinylidine fluoride (PVDF) were the least absorptive of the rigid tubing. In addition, they do not leach constituents into water. Of these, PVDF is the least expensive. Where a flexible tubing is necessary, such as the head of a peristaltic pump, fluoroelastomer tubing and a copolymer of vinylidine fluoride and hexafluoropropylene were much less sorptive than the other flexible tubing. They also leached the fewest constituents into the water. The copolymer is less expensive than the fluoroelastomer.

Wherever possible, dedicated sampling equipment should be used in each well. This prevents the possibility of cross contamination between wells. It also eliminates the cost of decontaminating the equipment between wells and the possibility of interference from solvents used for decontamination. Inexpensive disposable bailers are available and may be an acceptable sampling device for many studies where the cost of dedicated sampling equipment in each well is not justified.

8.6.5 Methods of Collecting a Groundwater Sample Without Drilling a Well

The installation of a monitoring well is a costly proposition, generally in the range of $5,000 to over $15,000 USD for shallow wells in unconsolidated materials. Moreover, the process can be disruptive to the property owner and can damage lawns and crops. At some sites there may be limited knowledge about the direction of groundwater movement and the existence and location of contaminated groundwater. The hydrogeologist may find it desirable to perform some type of screening investigation prior to the installation of permanent monitoring wells. During the screening the hydrogeologist may try to find the location and depth of groundwater contamination. There are devices that one can use to collect a groundwater sample without installing a monitoring well. These devices, as well as a standard sandpoint piezometer, can be used during the installation of a test boring.

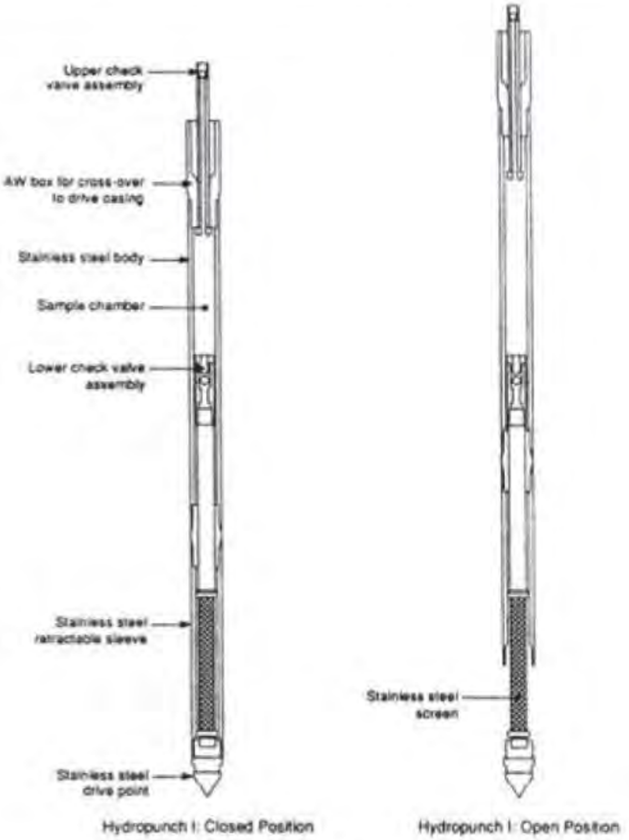
These methods all allow the collection of discrete samples in a vertical profile which gives one the ability to construct a vertical-concentration profile similar to that of a multilevel sampler. However, they have a drawback in that the samples cannot be replicated at a future date because the sampler is withdrawn after use.

The HydroPunch™ is one such device, a direct-push sampler, that can be used to collect a groundwater sample from a discrete depth in the earth (Edge and Cordry 1989). It consists of a pointed sampling probe that is attached to a hollow drill rod. The rod is pushed into the earth by the hydraulic ram of a drilling machine or cone penetrometer rig, or is driven into the earth by the dropping of a weight using a drilling machine. Such a device will obviously only work in unconsolidated materials. Moreover, HydroPunch I™ cannot be used in very coarse sediment. As a general rule, if a 2-inch split-spoon sampler cannot be driven into the earth, then the HydroPunch I™ will most likely be damaged if an attempt is made to drive it. A sturdier HydroPunch II™ has been made which can be used with cone penetometers or in conjunction with drill rigs. When the probe has been advanced to the target depth, the drive pipe is retracted about 1.5 ft (0.5 m). This raises a shield on the probe which exposes a stainless steel well screen that is 10 in. (25 cm) long. The probe has to be pushed at least five feet below the water table to completely fill the sampler. Hydrostatic pressure in the aquifer forces water to flow into the screen where it will rise into the probe until it reaches equilibrium with the hydrostatic pressure in the aquifer. Figure 8.32 illustrates the HydroPunch™ in both the closed and open positions. The screen openings in the HydroPunch™ are relatively large, and although water will enter relatively rapidly, the sample may be turbid. A check valve in the probe prevents water from draining back out of the screen and the entire assembly is withdrawn from the ground in order to retrieve the groundwater sample.

The BAT Enviroprobe™ is another type of discrete depth sampler (Mines et al. 1993). It is manufactured by Hogentogler & Co. Inc. of Columbia, Maryland. It is also pushed or driven into the earth to the desired depth by a drilling or cone penetrometer rig. When the drive pipe to which the probe is attached is pulled back about 1 ft. (0.3 m), a stainless steel sleeve is moved upward which exposes a 4-inch (10 cm) long screen. Figure 8.33 shows the BAT Enviroprobe™ in both a closed and an open position. There is a septum on the top of the screen which prevents groundwater from rising higher than the screen. The sample is collected by lowering a device with a double-ended hypodermic needle with an evacuated glass vial, which also contains a septum. The hypodermic needle penetrates both septa, and the water can move from the screen zone into the evacuated vial. The vial containing the groundwater sample is then withdrawn. Should this not contain sufficient sample volume, additional vials can be lowered through the riser pipe.

In the case of both the HydroPunch™ and the BAT Enviroprobe™, the water entering the screen is formation water and there is no need to either develop the well or purge it prior to sampling. This reduces the cost as the sample collection is quicker and also there is no contaminated purge and development water to dispose. Zemo et al. (1995) field-tested both the HydroPunch™ and BAT Enviroprobe™ and found that there was no statistically significant difference in trichloroethylene concentration found in

FIGURE 8.32 Closed and open position of the HydroPunch™ probe.



Source: Zemo et al. 1995. Field comparison of analytical results from discrete-depth ground water samplers. *Ground Water Monitoring & Remediation* 15:133–141. Used with permission.

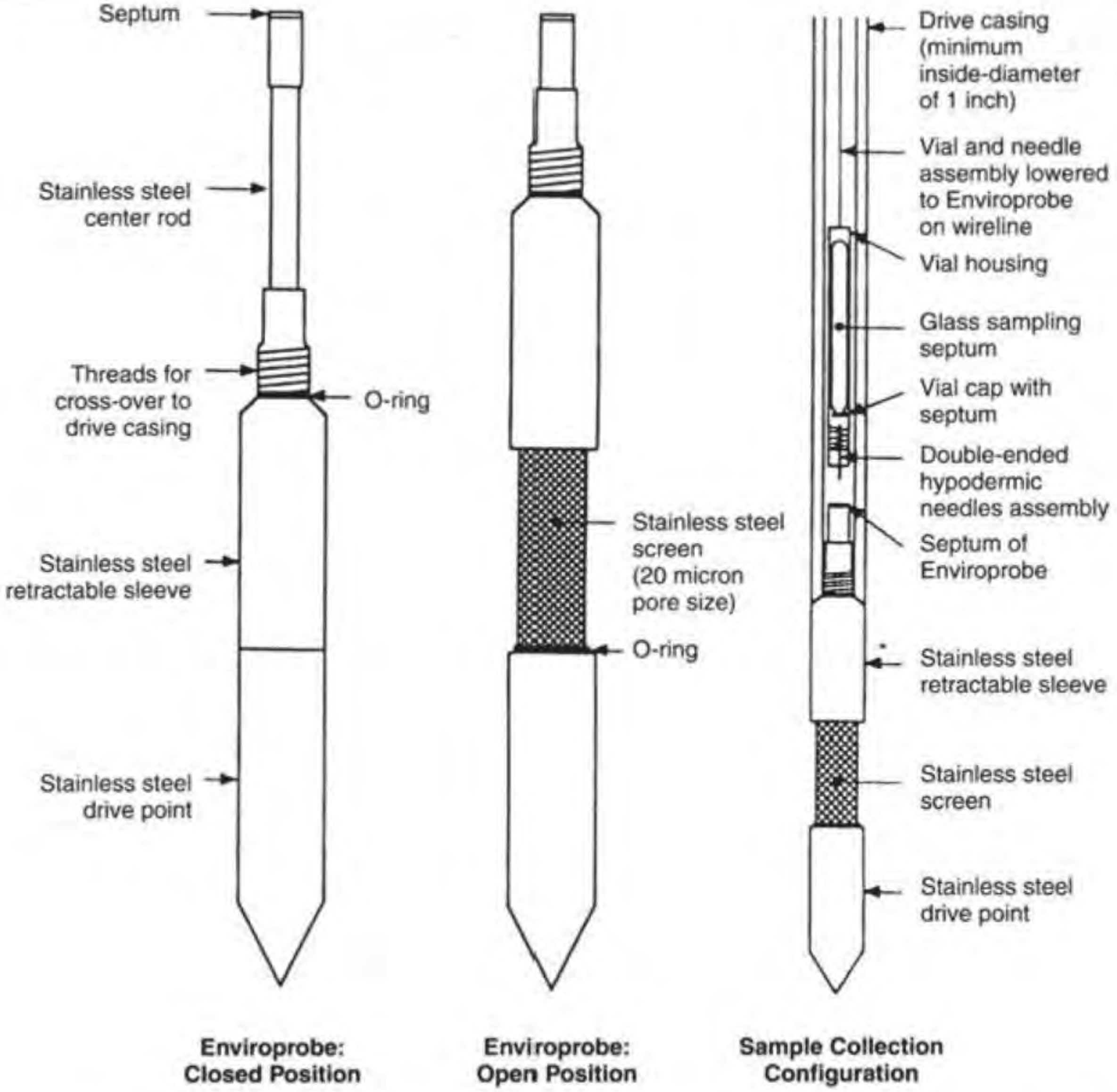
groundwater samples collected from either probe. However, they did find that there was a difference in chlorobenzene concentration. They were unable to determine why such a difference should exist.

If the unconsolidated material is too coarse for the sampling probes to be pushed very far into the earth, then they can be used with a hollow-stem auger drilling rig. The drilling rig is used to install a test boring. At selected depths, either probe can be advanced within the augers and ahead of the drill bit to collect a groundwater sample. This approach has the distinct advantage of gathering stratigraphic data along with water-quality data. In the absence of a specific sampling probe, a standard 2-foot long sandpoint piezometer can be driven ahead of the drill bit to collect a water sample. In this case a bailer is used to collect the groundwater sample. After the water sample has been collected, the device is withdrawn from the borehole and the augers advanced.

8.6.6 Low-Flow Purging of Monitoring Wells

An important advance in contaminant hydrogeology field methods is the development of micropurging or low-flow purging techniques (Puls and Paul 1995). The purging techniques presented in section 8.6.3 are designed to remove all of the stagnant water in both the screen and the casing above the screen. The micropurging technique withdraws

FIGURE 8.33 Closed and open position of the BAT Enviroprobe™ probe.



Source: Zemo et al. 1995. Field comparison of analytical results from discrete-depth ground water samplers. *Ground Water Monitoring & Remediation* 15:133–141. Used with permission.

water directly from the screen zone at a rate that is less than the recharge rate from the aquifer into the screen. The stagnant water in the casing does not mix with the fresh water entering the screen (Powell and Puls 1993). This purging rate is less than 1 L per minute; a suggested rate is only 100 mL/min. At this rate there is minimal drawdown in the pumping well and the water chemistry of the purged water tends to reach a constant value within one-half of a casing volume (Barcelona, Wehrmann, and Varljen 1994).

Micropurging is accomplished by using either a dedicated bladder or submersible pump with the intake set in the center of a well screen or a peristaltic pump with the end of the sample tubing set in the screen zone (Kearl et al. 1994). If a dedicated pump is not used, the pump should be placed in the well at least 24-hours prior to the time that the sample is collected. The purge rate should be about 100 mL/min, although somewhat higher rates could be used for very permeable formations. Two volumes of water contained in the pump and the tubing should be removed prior to collecting the sample. This will be much less than the volume of water in only one well casing. Samples do not need to be field filtered.

One of the problems that arises when sampling groundwater for metals occurs when the water sample is turbid. The turbidity is due to suspended mineral grains. These particles may contain sorbed metals. Some U.S. EPA programs and some U.S. state agencies prohibit the filtration of samples used for metal analysis as it is known that metals can travel in the groundwater with colloids (Puls and Powell 1992). However, turbidity in a sample can be caused by the process of lowering sampling instruments into the monitoring well (Kearl, Korte, and Cronk 1992) or by high screen-entrance velocities developed when significant drawdown occurs during purging. Micropurging techniques utilizing dedicated sampling equipment in each well will provide a sample with the least amount of artificially introduced turbidity. This will provide the best sample for use in determining total metals.

Kearl et al. (1994) compared samples collected by micropurging with samples collected by traditional purge and sample techniques. For most inorganic analytes and all organic analytes, there was no statistically significant difference between the two methods.

In addition to the ability to collect a nonturbid sample, there are other advantages of the micropurging technique. In some monitoring wells located in low permeability formations, traditional purging may withdraw most or all of the water from the well. This means that one must wait for a day or more for the well to recover enough water to yield a sample. This means that the sampled water was still stagnant for a period of time before being withdrawn. With a micropurging technique, a very low pumping rate could draw fresh formation water into the screen zone without much lowering of the water level in the casing.

There are two variable costs associated with groundwater sampling: personnel time and the expense of disposing of the contaminated purge water (Schilling 1995). With dedicated pumping equipment, the time for micropurging is generally less than that needed for traditional purge and sampling, hence the cost will be lower. The amount of contaminated water which must be disposed is much less in micropurging, hence the cost will be less.

While the impact of turbidity in a groundwater sample can have a significant effect on the concentration of metals in the sample, the same is not true for at least some chlorinated solvents. Paul and Puls (1997) examined the impact of sample turbidity on the concentration of trichloroethylene, cis-1,2-dichlorethylene and vinyl chloride. In both field and laboratory samples they found that solids entrained in the sample had no significant impact on the measured concentration of any of the three compounds. On this basis they concluded that turbidity in the sample does not appear to be of significance when sampling for VOC analysis. They did note that if the turbidity was the result of sample agitation that factor might result in loss of volatiles.

8.6.7 Sampling Frequency

Groundwater sampling is carried out commensurate with efforts to understand the nature and extent of groundwater contamination, predict future movement, ensure that harmful excursions of pollutants do not occur, facilitate remediation, and other goals pertinent to site characterization. Many regulatory agencies specify and sometimes codify periodic time frames for sampling of monitoring well arrays, such as monthly, quarterly, or annual sampling. These periodic samplings have the benefits of allowing practitioners to predict many costs in advance, and look for long-term trends in water quality. From a regulatory standpoint this makes sense, although natural events that can alter water quality are not always periodic. For example, in karst systems great changes in subsurface water quality can occur during pulse flow events, and perhaps in many cases the best monitoring strategies for cave systems include sampling immediately before, during, and after intense rainfall and infiltration. Regulatory monitoring requirements are sometimes wrongly viewed as the maximum effort necessary to understand and deal effectively with groundwater contamination, particularly if monitoring costs are to be minimized. In reality, although standardized monitoring intervals make regulatory expectations clear, a one-size-fits-all sampling frequency is not always the best way to understand subsurface contamination at a particular site. Long-term costs are typically reduced with a clear understanding of contaminant distribution and movement, and sometimes this necessitates more frequent, strategic sampling before remedial action and site closure is attempted.

8.7 Other Site Characterization Methods and Groundwater Contamination Forensics

8.7.1 Introduction

Site characterization is much more than just identifying groundwater pollutants and measuring their occurrence in the subsurface. A challenge is that many well-defined characterization goals and objectives require a deep understanding of a site's geology, an understanding of groundwater travel times, knowledge of the chemical characteristics of potential contaminants, and awareness of logistical and safety concerns, just to name a few necessities. These complex objectives are often resolved by geologic testing, detailed environmental chemistry analysis, and environmental forensics.

There are many wide-ranging applications of site characterization techniques and groundwater forensics that support a robust understanding of source water protection, the potential for contaminant movement and transformation, groundwater vulnerability, and the integrity of aquitards or barriers which are relied upon to isolate waste. Numerous monitoring and characterization techniques have been, and continue to be developed, adding to the arsenal of methodologies to characterize subsurface contamination, and many of these methods rely on probes to be driven into the subsurface, measurements to be taken from boreholes, or samples to be taken from wells. In some cases contamination can be suspected based on field conditions. Field observations for NAPLs illustrate this point. For example, if DNAPL chemical concentrations in groundwater increase with depth in a pattern inconsistent with advective groundwater flow, or increase counter to a hydraulic gradient, there is support for the possibility of DNAPL being spread in its free phase. Other indicators of free-phase NAPL include situations where the aqueous concentration of NAPL compounds in groundwater is greater than 1% of the pure phase (for a single NAPL compound) or effective solubility limit (for NAPL mixtures). Note that the opposite is not true; concentrations below 1% may or may not be associated with free-phase NAPL. In soils where NAPL concentrations are greater than 10,000mg/kg (1% of soil mass) free phase can be suspected. Other qualitative signs of free-phase NAPL include erratic concentrations of NAPL chemicals in groundwater, soil, and soil gas; rebound of elevated dissolved NAPL concentrations after a pumping system is turned off; the presence of DNAPL chemicals in groundwater that is older than potential release dates; and observed deterioration of pumps and well components.

Quantitative methods can often be used as evidence in legal proceedings and the field of environmental forensics is based on efforts to distinguish pollutant sources (Morrison and Murphy 2006). Environmental forensics is defined by Hester and Harrison (2008) as "a combination of analytical and environmental chemistry, which is useful in the court room context. It therefore involves field analytical studies and both data interpretation and modeling connected with the attribution of pollution events to their causes." There are a vast number of techniques to determine the source and pathways of groundwater contamination that fall into the realm of forensic hydrogeology.

8.7.2 Borehole Geophysics and Downhole Techniques

Many geophysical techniques originally developed for oil and gas exploration are often used in drilled boreholes to define subsurface geology and hydrogeology, directly identify pollutants, and/or understand the potential movement and distribution of contamination. Downhole logging approaches will "ground truth" surface geophysical techniques and results can be directly compared to borehole cuttings or core samples. Like borehole cuttings and core, downhole geophysics provides vertically continuous data, but geophysical methods sample a greater subsurface volume with relatively little bias. As more boreholes are logged at a site and cross-borehole techniques are used, 3-dimensional imaging techniques (tomography) can assist visualization of contaminants and subsurface geological structures, faults, and formations (Obiadi et al. 2012). Downhole surveys have assumed great importance in contaminant site surveys because the specific site characteristics and heterogeneities in porous media and fractured rock can profoundly influence the distribution and the potential for remediation for a host of contaminants. Borehole geophysics can provide information directly applicable to site characterization, including delineation of hydrogeologic properties, subsurface water quality, and determination of a well's construction, status, and condition.

Physical, Visual, and Acoustic Borehole Geophysics Several techniques can measure the physical, visual, or acoustic properties of boreholes. One of the most straightforward downhole techniques is television (TV) logging where a color optical image is made of the borehole walls. This is particularly effective in identifying and characterizing fractures in hard rock materials, but can also identify lithology, water level, cascading water from perched zones (which could transmit contamination vertically), well construction failure, and water quality indicators such as suspended particles, gases, and chemical precipitates. TV logging can be viewed real-time and/or be stored and archived, and cameras and focal lengths can be adjusted to view either straight downhole, angled, or side-looking for inspection of borehole walls. An extension of TV logging is acoustic-televiewer logging which records a photographic, digital image of the acoustic reflectivity of the borehole, oriented magnetically. These televiewer logs are used in water or mud-filled open holes, and can identify geologic contacts between different strata, and fault location, strike, and dip. Televiewers use a rotating transducer which can transmit and receive many samples per revolution and have azimuthal information from magnetometers on the device. This acoustic or sonic logging can help determine the porosity of a rock, aid in identification of lithology, facilitate estimation of secondary porosity and fracturing, and help assess rock permeability. Seismic logging, which transmits sound at lower frequencies, can be extended to cross-borehole tomography where images of seismic velocity between boreholes is generated, and geologic and hydrologic properties between the boreholes can be better understood.

Another type of physical downhole measurement is a caliper log which measures the varying diameter of an uncased borehole. Variable borehole diameter can indicate the potential for material to fracture or slough away from the walls and into a borehole, and therefore be a sign of media which may transport contamination. Alternatively, hydrogeologically transmissive zones can be directly identified with flowmeter monitoring. Vertical flowmeter testing in a single hole involves moving a flow measuring device up and down a hole during pumping or during nonpumping times, pinpointing zones of high and low groundwater transmissivity. Single-hole flow metering can also measure the rate and direction of vertical flow which can cause pollutants to migrate, and show relative vertical hydraulic gradients. In cross-hole flowmeter profiling, a flowmeter is placed in one hole while water is added or withdrawn from another borehole at a constant rate, allowing calculation of transmissivities, head differences, or storage coefficient between the boreholes. Packer systems (see section 8.4.9) can further isolate individual fractures and/or test hydrologic properties at individual depths between holes. Impeller flowmeters (rotameters, spinners) are most commonly used for these measurements, but have less resolution than heat-pulse or electromagnetic flowmeters. Vertical measurement of water temperature in a borehole can also be useful. These temperature measurements can define hydrostratigraphic layers, vertical flow, and water-bearing zones. Vertical borehole flow is implied by temperature gradients that are inconsistent with the regional geothermal gradient which is typically about 2.5°C per 100 m (1°F per 70 ft.). Distributed temperature sensing (DTS) has been used in boreholes to delineate hydrostratigraphic heterogeneities by synoptically profiling temperature distribution changes from thermal dilution tests. These tests do not disturb the fluid column (Leaf, Hart, and Bahr 2012).

Gamma and Neutron Logging Other borehole logging techniques are useful in site characterization. Downhole gamma logging records the amount of natural gamma radiation emitted by a formation in the vicinity of a borehole. Specific sources of gamma emission are potassium-40 (^{40}K) and daughter products of uranium and thorium decay series which are common in clays and shale. This is because these geologic materials contain weathered products from potassium feldspar and mica, and are apt to concentrate uranium and thorium. Importantly, clay and shale typically have low permeability and are barriers to contaminant flow. Another technique, neutron logging, measures the amount of water in any particular vertical section of borehole. Energetic or "fast" neutrons are sent out into the formation surrounding the borehole usually from an Americium Beryllium (Am-Be) or Plutonium Beryllium (Pu-Be) source, and these neutrons are slowed down by collision with hydrogen ions associated with water. The returning "slow" neutrons are measured by a detector and indicate water bearing strata in the vadose zone, and water-filled porosity below the water table.

Electrical Techniques in Borehole Geophysics Several borehole electrical techniques are available for site characterization. These include single point resistance logs, normal-resistivity logs, spontaneous-potential logs, electromagnetic induction logs, and fluid-resistivity logs. Single point resistance logs measure the electrical resistance between selected points in the borehole and an electrical ground on the surface, and are useful for understanding lithology, water quality and the amount of fracturing in hard rocks. Interpretation involves identifying zones of increasing resistance associated with small diameter boreholes, whereas lower resistance is related to saline water, large borehole diameter, and highly fractured media. Normal-resistivity logs record the resistance to electrical flow immediately outside an open, uncased borehole, and interpretation generally is similar to that of single point resistance measurement. Normal-resistivity logs typically involve deployment of a string of vertically displaced electrodes in a single hole.

Electromagmetic-induction (EM) logs also measure electrical conductivity or resistivity immediately outside a borehole and are excellent for indicating porosity, permeability, clay content, and total dissolved solids in fluids. Further, EM and other electrical techniques are proficient in identifying landfill leachate and saline water intrusion. EM borelog techniques are designed to optimize readings outside the borehole and minimize influence of the borehole and borehole fluids. Conversely, fluid-resistivity logs are geared toward examining borehole fluids, particularly the dissolved salt and solid concentrations.

Other Borehole Geophysical Techniques One versatile monitoring procedure for organic compounds is laser induced fluorescence (LIF) that uses laser light to excite fluorescent molecules in petroleum products. The excitation is specific for PAH compounds, but nearly all petroleum products contain some PAHs. LIF field measurements utilize a direct push logging arrangement which allows vadose zone and aquifer material to be examined at depth below ground surface. Further, LIF can distinguish different NAPLs in the subsurface using the intensity of the fluorescence in the media, its spectral signature, and the lag time between the laser pulse and emission of fluorescence. The laser light is transmitted down and uphole by two separate fiber optic threads, and the signal is processed and analyzed in real time.

Fiber optic chemical sensors (FOCS) are a variant of LIF and have been developed using a sensor for analysis of soil, air, or water that records changes in light absorbance, reflectance, fluorescence, and light polarization of the medium. Unlike LIF which just uses fiber optics to transport light down and uphole, FOCS uses the fiber optic cable as an integral part of the sensor. Specifically, part of the fiber optic cladding is removed from the cable in the sensor and replaced with a chemically selective layer that, when placed in the sample media, reacts with a specific analyte of interest. Raman spectroscopy is used to identify specific metals and organic chemicals. The detection limits are typically in the ppm range for VOCs.

8.7.3 Water Quality Indicators of Groundwater Provenance and Movement—Tracers

Beyond sampling water for contaminant concentrations and conducting geophysical surveys for defining subsurface geology, there are many other methodologies and water-quality indicators pertinent to site characterization. The chemical mixtures in measured contaminants and certain characteristic compounds (or "tracers") can be key indicators of pollutant source, travel pathways, and transformation. Tracer techniques for groundwater can be divided into water quality surrogates that are either (1) chemicals added to aquifer systems or to potential contaminants in regions where subterranean flow is expected to be rapid, or (2) "environmental tracers" which are groundwater quality changes which have occurred over longer periods of time in groundwater. The former includes dyes and chemicals intentionally added to track movement and flow, and the latter refers to "natural or anthropogenic compounds or isotopes that are widely distributed in the near-surface environment of the Earth, such that variations in their abundances can be used to determine pathways and timescales of environmental processes" (Cook and Böhlke 2000).

Payne et al. (2008) and Suthersan et al. (2014) present guidance for tracer selection, tracer test design, and data interpretation. An optimal groundwater tracer is highly detectable, mimics either groundwater or pollutant movement, is chemically stable for a desired length of time, has little background concentration in the groundwater being investigated, is not sorbed or filtered by the geologic media, and does not have adverse health or ecological effects (Davis et al. 1980). Conservative compounds that are not sorbed or retarded in their flow are particularly useful and these include chloride, bromide, iodide, nitrate, sulfate, and boron. These compounds can reflect groundwater origins with less ambiguity than other dissolved species, because they are often present in groundwater and some, like boron, are relatively unaffected by evaporation or chemical reactions (Barth 1998; Bassett et al., 1995; Vengosh 1998).

Dyes and Injected Tracers, Artificially Introduced Tracers In many fast-flowing (e.g., karst, carbonate rock, and caves) groundwater systems, tracer dyes can be released to track direction and travel times of flow. Optimal systems typically transmit water and pollutants quickly, which is advantageous because a long waiting time for the re-emergence of injected tracers is not favorable. Tracers can be artificially injected into wells, sinkholes, caverns, and disappearing streams in karst terrain. Popular tracer dyes include fluorescent dyes such as fluorescein which was developed over 145 years ago, pyranine, lissamine FF, photine CU, amino G acid (7-amino 1,3 napthalene disulphonic acid), optical brightners, and a variety of rhodamine dyes. A downside of some of these dyes is that some have negative health effects. Dyes can be used either qualitatively by visual observation, or collected with adsorbing devices to quantitatively measure flow. A simple adsorption apparatus involves placement of a charcoal packet along expected pathway of subterranean flow. More sensitive devices include filter fluorometers and spectrofluorometers which can determine specific fluorescent wavelengths, quantify flow more accurately, and distinguish background fluorescence and other interferences. In addition to the tracing of natural waters, dyes can help determine pipeline leaks. Nonpolar fuel dyes can be added to demarcate different fuel types and are required in some countries. This can help distinguish the individual impacts of multiple fuel leaks of similar types, but from different sources.

Things other than dyes can be injected as tracers of groundwater flow. A common tracer for groundwater is chloride (Cl^-) which is a component of common table salt. Care must be used when using ionic tracers so that the concentration of salts added to groundwater does not change its density and subsequently impact natural groundwater flow. A more unusual tracer that has been used in cave systems is a signal emitting float which has a delayed explosion. The seismic signals emitted from these generated impulses can help locate subsurface passages. Other tracers that have been used with varying degrees of success include silicic acid, boric acid, phosphoric acid, acetic acid, alcohols including ethanol, sugars (sucrose, maltose, dextrose, glucose), and glycerol (Davis et al. 1985). Each of these tracers has disadvantages: acid can react with aquifer material, sugars decompose rapidly, and alcohols tend to be absorbed onto organic material (which can actually be used to advantage by measuring partitioning into suspected organic contaminants).

Tracers developed for contaminant hydrogeology include a class of compounds called partitioning tracers. These newer methods involve circulating a suite of tracer compounds, not just a single tracer, in the subsurface to measure how some tracers are slowed by contaminant mass, particularly a mass of nonaqueous phase liquids. Partioning tracers measure groundwater flow and the mass of a stagnant immiscible liquid pollutant blocking groundwater's path by observing the differential tracer retardation. The underlying principles of this tracer method have been discussed in Chapter 3.

Scientific developments include the study of colloidal tracers and smaller, nanoparticle tracers. These colloidal tracers have included yeasts, bacteriophages (viruses), fluorescent latex microspheres, bacteria (living and dead), spores (Lycopodium and vegetative spores), and other nanoparticles (Davis et al. 1980; McKay et al. 2000; Zhang et al. 2015). Solid tracers are larger than dissolved aqueous tracers and have the negative possibility of being sieved or filtered through porous media and small-aperture fractured media. Larger particle tracers do, however, have the positive quality of not being absorbed in the rock matrix. Occasionally, solid tracers have been observed to move faster than average groundwater velocity—this has been explained by the notion that larger particles move through larger pore spaces or fracture apertures where groundwater velocities are higher than average (Zhao 2015).

Gases can be used as tracers of vapor migration, and of liquid migration by injection and dissolution of gases into groundwater. Inert radioactive tracer gases have been considered, such as xenon (^{133}Xe) and radon (^{222}Rn), particularly in identifying groundwater/surface water interaction, but health concerns and a short half-life for radon are inhibitory (Xie et al. 2016). Noble gases of helium, neon, argon, krypton, and xenon are other potential tracers as their natural background in the environment is low. Chloroflourocarbons (CFCs or Freon® compounds), also have low environmental background and have been used for both groundwater and gaseous tracer experiments (Thompson et al. 1974, Weeks et al. 1982; Kreamer et al. 1990).

Environmental Tracers Environmental tracers which show water-quality patterns and changes do not have to be injected by site investigators, and are directly relevant to understanding a contaminated site. Some of these tracer signals arise due to natural fluctuations in local, regional, or global conditions, while others reflect anthropogenic influences and activities. Some take advantage of short term changes. For example, diurnal temperature fluctuations can be used to define gaining and losing reaches of streams. Probes placed in bottom sediments of streams that show daily temperature variation can be associated with losing reaches as water, affected by daily conditions, infiltrates. Conversely, steady temperatures in stream bottom sediments can be indicative of a gaining groundwater contribution to a stream through the sediments, as most groundwater is typically more constant in temperature. Other tracer signals arise from longer-term changes in climate, recharge differences, or substances that humans introduced into the environment decades ago. Compounds and isotopes that have leaked into the atmosphere from human activities (e.g., chlorofluorocarbons from refrigerants, radionuclides from testing of nuclear weapons) return through rainfall to the vadose zone and groundwater, and allow dating of groundwater age, whereas pharmaceuticals, personal care products, and specific compounds in some foods (e.g., caffeine) are not readily removed by sewage treatment and become tracers of wastewater release into the environment.

The source of a pollutant strongly influences its chemical makeup, and chemical differences from dissimilar sources can be used to trace and track environmental contamination. Biogenic gaseous mixtures containing methane are typically "dry" which means a higher concentration of methane and light hydrocarbons, whereas thermogenic gases and those from pipelines have less light 2 to 4 carbon compounds (C2s to C4s) and are "wet" with a higher concentration of 5 carbon (C5) and higher molecular weight compounds. Landfill gases are often approximately half methane and half carbon dioxide with an absence of oxygen. Natural gas derived from dewatering of coal layers, an extraction process whose retrieved product is called "coal seam gas" or "coal bed methane," is typically higher in methane than natural gas extracted from other sources and is therefore sometimes called "sweet gas." Crude oil and coal from different regions of the world have different chemical constituents which can be tracked, for example differences in the amount of sulfur compounds designates different quality of crude oil. The petroleum industry has noted that uptake of sulfur into plants is possible. Because different isotopes of sulfur can fractionate in different ways, the transport and fate of sulfur bearing compounds can be further tracked. Also, natural gas in pipelines in municipal and urban settings typically has noxious smelling mercaptan added so that leaks of this normally odorless gas are readily noticeable and are often reported. The added gases which allow leak detection and tracking sometimes have descriptive names like Cadaverine and Putrescine.

Human sewage and animal waste have a host of associated compounds and microbes which can be used to track their contamination in groundwater systems. Bacterial indicators, like Escherichia coli (*E.coli*) are useful, but often can be filtered out in porous media, whereas bacteriophages and human viruses are smaller and can travel farther. When microbes occur in groundwater they can indicate source by phenotype, genotype, and speciation (some microbes are more associated with human waste and others with ruminant species). Some genera and species of bacteria studied as indicators differentiating human from other mammalian waste include: *E.coli*, relative amounts of fecal streptococci and fecal staphylococci, *Bacteroides* spp., *Rhodococcus coprophilus* (animal herbivores), *Clostridium perfringens*, *Bifidobacterium adolescentis* (human), and *Bifidobacterium thermophilum* (animal). Other tracers of human and animal waste include: sterols, steroid estrogens (found in human sewage outfall), fatty acids and lipids, surfactants and detergents, caffeine (human ingestion and sewage outfall), triclosan (an antibacterial and antifungal agent found in hand soaps, body washes, toothpastes, and some cosmetics—sewage outfall), and sewage/septic tank related nonylphenol ethoxylate metabolites (Swartz et al. 2006).

Ionized substances have been used both as artificially injected tracers and measured as natural environmental tracers indicating source. There are a large number of ions which can be tracked and traced, and these substances do not decompose with time. Historically, those chemical species with high concentrations, easy detection, and low sorption have been the most popular. This includes negatively charged anion species which are repelled by negatively charged clay surfaces and therefore resist sorption. Traditional tracer ions include Cl^-, Br^-, Li^+, NO_3^-, NH_4^+, SO_4^-, Mg^{++},K^+, B, and I^-. Of these, Cl^- and Br^- are the most popular. Organic anions have been used as tracers, including benzoate. Metal complexes with chelating agents have been used to track groundwater flow, balancing the need for a detectable tracer with the potentially negative health effects of mobilizing a heavy metal pollutant (Davis et al. 1980). With the advent of Inductively Coupled Plasma Mass Spectrometers (ICP-MS) investigations of naturally occurring trace elements to identifying groundwater pathways increased (Stetzenbach et al. 1994; Kreamer et al. 1996; Johannessen et al. 1997).

Importantly, CFCs have also been used for dating recharge from precipitation, because the first wide use Freon® refrigerants began after 1930, and subsequently increasing amounts of gaseous CFCs leaked into the atmosphere and mixed with precipitation, eventually infiltrating the ground surface and recharging groundwater. CFCs were also used as aerosol spray can propellants, but because they contribute to ozone layer depletion in the atmosphere, their use has been phased out under the Montreal Protocol. CFCs are greenhouse gases with an approximate residence time in the atmosphere of 65 to 130 years and their abundance or absence in groundwater is an indicator of groundwater age. The ratio of CFCs to SF_6 (sulfur hexafluoride) has a groundwater dating age range of about 1 to 40 years.

8.7.4 Water Quality Indicators of Groundwater Provenance and Movement—Groundwater Composition, Compound Ratios, Daughter Products, Degradation Indicators, and Other Indicator Compounds

A considerable number of methods to track, trace, and date groundwater contamination rely on looking at the changing composition of pollutant compounds, associated chemicals, and differences in the chemical nature of multiple sources. Identifying and utilizing compositional differences is a powerful tool in understanding groundwater and contaminant flow.

Inorganic Indicators One of the simplest ways to distinguish different sources and transformation of contaminants is by analyzing groundwater chemical quality and compound ratios. Significant analytical chemistry advancements have been, and continue to be, made since major anions and cations were first measured in groundwater, but these ions, and the ratios between these ions (particularly the more mobile anions) continues to be a source of groundwater definition. Piper, Stiff, and Maucha diagrams visually portray the major ionic components of water quality and can indicate groundwater provenance. Ratios of ions can also be used to distinguish waters. For example, a common anion comparison used to trace groundwater has been the Cl^-/Br^- ratio. Davis et al. (1998) report on many of the uses and applications of this ratio, including determining the origin and evolution of salt water and brines, and studying salt in potable groundwater. Factors which can affect this ratio include distance from the ocean, dry lake beds, or other sources of salt, including pollution (Davis et al. 2004; Alcala and Custodio 2008). These ratios have been used to track septic tank pollution in the United States (Katz et al. 2011). Other useful ratios are total inorganic carbon to total organic carbon ratios, and carbon to nitrogen ratios.

Mining operations for various metals often can have more than one metallic species that can enter groundwater, or mobilizing agents and additives associated with the particular extraction method and target metal. These other species and additives can often be used to track the influence of mining operations on groundwater systems. Several metals, metalloids, and nonmetals can often be found together in metal extraction and mining (e.g., it is possible to observe combinations of uranium, copper, arsenic, gold, silver, vanadium, sulfur, thorium, lead, zinc, or others from some precious metal operations). Other types of mining undertakings have other potential tracers released into the environment. *In situ* leach mining typically uses an injected lixiviant to dissolve and mobilize extractable metals, and these lixiviants can be used as one indicator of potential contaminant migration, with the cautionary note that while a rapidly moving lixiviant can give early warning of potentially slower-moving contamination, the disappearance of the lixiviant does not necessarily indicate the disappearance of the spectrum of potential groundwater contaminants at a mining site. Metals can also be used as surrogate tracers for energetic compounds, that is propellants, explosives, and pyrotechnics (PEP) compounds. For propellants and some fuels particularly linked with the rocket fuel oxidizer perchlorate, Cr^{+3}, Cr^{+6}, Cu^{+2}, and Zn have been evaluated as surrogates. Surrogate compounds in fireworks and flares include Na, K, Ba, Cu^{+3}, Sb, Sr, Al, As, and Cr^{+5} (Motzer 2001).

Organic Indicators Organic compounds, particularly mixtures of organic chemicals, have a wide range of sources, additives, and degradation products which can be tracked in groundwater (Chapter 7). The differing rates of degradation of the compounds in subsurface organic mixtures produce changes in the ratios of those compounds and of generated daughter compounds. Many organic mixtures have unique source compositions and all eventually weather and transform with time. Hydrocarbon fuels in particular have different compositions, depending on fuel type and additives. These differences serve as distinguishing features when several different fuels have leaked or have been spilled. Fuels and oils normally consist of mixtures of hundreds of compounds, and different fuel types have different dominant ranges in the number of their carbon atoms. Crude oil has compounds that range from having one or two carbon atoms (C1 and C2) to compounds with close to sixty (C60). Crude is fractionally distillated to establish different types of hydrocarbon products, and different additives are put in for these varied purposes. Gasoline for cars (petrol) and small airplanes (aviation gas or AV-gas) typically have light hydrocarbons predominantly ranging from the 4 carbon compounds (C4) to about the 11 or 12 carbon range (C11 to C12). Kerosene is a heavier fuel with approximately the C8 to C17 compounds, diesel fuels are roughly in the C8 to C24 range, the jet fuel JP-4 is about C5 to C14, and JP-8 and Jet-A approximately C8 to C18. Stoddard solvent, which was used in the past as a dry cleaning fluid, has a typical petroleum distillate fractions of C7 to C12, heavy fuel oils are generally between C8 and C50, bunker fuel used in ships are approximately C10 to C26, and lubricating oils are even heavier with carbon numbers around the C14 to C50 range. Other residuum from crude distillation often have more than 20 carbon atoms in their constituent compounds, with waxes ranging approximately from C20 to

Darrah et al. 2013). Recently, examining methane in concert with noble gases in stream beds has been used to identify thermogenic methane fluxes from groundwater overlying regions of shale gas development (Heilweil et al. 2015). Methane isotopes as well as dissolved organic carbon and tritium have been use to evaluate connectivity between aquifers and underlying coal seam gas operations (Iverach et al. 2015).

Quantifying the uptake of nutrient compounds during biodegradation and the resultant production of daughter products and residuals are ways to monitor the rates of transformation of organics. Petroleum degradation is normally an aerobic process which uses oxygen and produces carbon dioxide; by monitoring the extent of change in these compounds one can calculate the rate of biodegradation and, importantly, determine whether the plume is moving faster than the rate of natural or augmented pollutant attenuation.

Harmful compounds can have additives or impurities which are not only good tracers in the environment, but they can be pollutants in their own right. Chlorinated solvents have several stabilizers. For trichloroethene (TCE), 1,4 dioxane is an important stabilizer used to facilitate transport and storage in aluminum containers. It is itself considered a solvent with negative health effects. The ratios of the chlorine-35 to chlorine-37 can be another way to fingerprint chlorinated solvents. Another example of mixtures and impurities is polychlorinated biphenyls (PCBs) which are never a pure, single compound, but mixtures of PCBs by the nature of their manufacture. PCBs can also have co-contaminants of polychlorinated dibenzofurans and polychlorinated naphthalenes. The nature of the mixtures can be a good source of differentiation, and the disparity in the degradation rates of contaminants, additives, impurities, and inert compounds can indicate age and source.

Historically, pesticides were mixed with some hydrocarbon fuels to apply them to crops. Many of these pesticides have comingled substances (some inert) and trace substances (e.g., dioxins and furans) which can help fingerprint their spatial distribution at a site. Like PCBs above, the source and age of pesticide releases can be established by comparing the ratio of inert and degrading compounds.

8.7.5 Water Quality Indicators of Groundwater Provenance and Movement—Isotopic Identification of Pollution Sources and Groundwater Pathways

The measurement and evaluation of stable, radioactive, and radiogenic isotopes has played an important role in hydrologic and geologic investigations, and are equally consequential in the characterization of contaminated sites. Because physical, chemical, or biological transformation of a contaminant can alter the compound's original isotopic ratios (fractionation), transformation processes can often be distinguished from contaminant dilution (which typically does not alter these ratios). The mathematics of Rayleigh distillation to quantify isotopic fractionation accompanying phase changes and chemical reactions are well known, and make available numerical estimates of the magnitude of isotopic change. The analytical detection of isotopes in groundwater and vapors is rapidly advancing, with the required sample volumes becoming smaller, and analyses becoming faster, less expensive, and routine. From older methods like scintillation counting of radioisotopes which required large volumes of water, through isotope ratio mass spectrometry advances, to new analytic techniques such as Laser Isotope Ratio Infrared Spectrometry IRIS, which can be portable and field deployable, the analytical chemistry underpinnings of contaminant surveys has increased the ability of the contaminant hydrogeologist to assess a site and its properties. Accelerator mass spectrometry (AMS) can sometimes separate atomic isobars (for example nitrogen-14 from carbon-14) and makes possible the detection of many isotopes, including many that are long-lived. AMS has been applied to the analysis of many isotopes including ^{36}Cl, ^{10}Be, ^{14}C, ^{3}H, ^{129}I, ^{26}Al, ^{236}U, ^{240}Pu, and ^{210}Pb.

Applications of isotope hydrology to challenges of groundwater movement and source are numerous, diverse, and are used worldwide. Isotope hydrology has been used to ascertain renewable and nonrenewable, deep groundwater in Syria (Al-Charideh and Kattaa 2016), the origin of groundwater in the Negev Desert (Vengosh et al. 2007), preferential flow along faults in Germany (Gumm et al. 2016), altered spring flow quality in Grand Canyon National Park in the United States (Ingraham, Zukosky, and Kreamer 2001), assessment of fluid inclusions at the proposed nuclear waste repository at Yucca Mountain, Nevada, as evidence of a hypogene paleohydrogeological event (Dublyansky and Spötl, 2010), baseline measurement and assessment of methane concentrations of a well in Alberta, Canada (Humez et al. 2016), and has been employed for countless other assessments at locales around the globe.

Tracing Groundwater and Pollution with Isotopes More than fifty years ago, paleoclimatologists and environmental geochemists began using the stable isotopes of hydrogen and oxygen to track meteoric water movement on the environment (Craig 1961; Dansgaard 1964). An equation showing the average relationship between these isotopes was established (the global meteoric water line) and variations due to temperature, seasonality, precipitation and recharge altitude, latitudinal relationships, and paleo-effects were key in understanding global water movement, including groundwater source and pathway. Because surface waste impoundments (ponds, pits, and lagoons) have the potential to partially evaporate water, then have the remaining surface water leak into the subsurface, isotopic fractionation during evaporation of water is particularly important to contaminant site characterization studies. Evaporated water has a lighter isotopic composition, enriching the remaining liquid with heavier isotopes which can often be tracked into the subsurface, distinguished from background groundwater isotopic signatures, and used to establish mixing ratios of leaked, contaminated water to natural background groundwater signatures. For very old groundwater, past climatic change can be observed and contribute to studies of aquifer isolation and aquitard or aquiclude integrity. Aquitard integrity and the origin of pore water has been investigated in Canada for mining operations and potential nuclear waste storage by comparing Pleistocene age versus modern stable isotope ratios, below and above thick aquitards (Hendry et al. 2013; Hendry et al. 2015). The stable isotopes of water are hydrogen and deuterium, and oxygen-16 and oxygen-18.

The stable isotopes of nitrogen (nitrogen 14 and 15) in concert with those of oxygen have been used to discern anthropogenic sources of nitrate, nitrite, and ammonium in groundwater. These contaminant sources can include septic tank effluent or wastewater, animal manure, and mineral fertilizers, and can often be distinguished by isotopic ratios. Because there is some overlap and ambiguity between isotopic composition in wastewater and animal manure, and denitrification processes in the subsurface can result in fractionation after nitrate release, additional indicators can be used to help tell different sources apart. Distinguishing co-contaminants from agriculture can include herbicides, pesticides, and major ions and trace elements from soil amendments. From wastewater, co-contaminants can include pharmaceutical compounds, residuals from personal care products, caffeine, and artificial sweeteners. Some animal feeds contain unique inorganic additives as well. Relatively conservative stable isotopes of boron (10 and 11) have also been used to make a distinction between wastewater and animal manure (Eppich et al. 2012). In China, stable isotopes of hydrogen, and oxygen and sulfur have been used to delineate the sources of anthropogenic nitrate and sulfate groundwater pollution (Li et al. 2006). Sulfate isotopic values indicated much of the pollution came from recharge of air pollutants from the combustion of coal, with some contribution of sulfur additives in fertilizer.

Mining residuals and mineral waste products can be distinguished by isotopic analysis. In uranium oxides, stable isotopes of oxygen can help distinguish anthropogenic mining activities from natural background as can activity ratios of uranium-234 to uranium-238. $^{234}U/^{238}U$ ratios are close to 1, (secular equilibrium) near uranium mining outfall, whereas naturally occurring uranium background in groundwater often has a higher ratio, particularly in old groundwater. Conversion of ^{238}U to ^{234}U can further be examined by its concurrent production of alpha particles, ^{4}He. Another isotope, uranium-236 is dominantly anthropogenic, is found in spent nuclear fuels and some reprocessed uranium, and can therefore help trace nuclear waste leaks. Plutonium (Pu) is also of human manufacture, and while trace amounts can be found in nature (parts per trillion in groundwater) larger concentrations of this fissile material indicate contaminant excursion. A potential nuclear waste product and tracer is technetium-99 which is the most significant long-lived fission product of uranium.

Other mining and industrial by-products, including metals and salts, can be characterized with isotopic analysis, sometimes in conjunction with other approaches. For example, stable isotopic analysis of chromium species in groundwater can give a picture of the natural reduction of mobile and harmful Cr(VI) to less problematic Cr(III). It can also characterize the extent and rate of Cr reduction during remedial activities. Another industrially produced compound which has been found in groundwater, and is an endocrine disruptor in humans, is perchlorate. Perchlorate has some naturally occurring salts, but is mostly generated by industrial processes especially for the production of rocket fuel oxidizers. Tracking the compound in the environment has included measurement of the oxygen and chlorine isotopes of perchlorate itself as well as other isotopic ratios and attendant compounds. Other useful isotopic analyses for perchlorate tracking are stable isotopes of strontium, nitrogen, and tritium, and isotopic ratios of $^{37}Cl/^{35}Cl$, $^{87}Sr/^{86}Sr$, and $^{16}O/^{17}O$. Some of perchlorate's additional surrogates in groundwater that can assist in source identification and age dating include: nitrates, sodium, chlorides, strontium, phosphate, metals, and nitroglycerins (Morrison and Murphy 2006). These methods can help determine whether perchlorate in the environment is natural or synthetic.

Isotopes and Groundwater Dating Isotopes are also used for characterizing the fate and transport of organic compounds. Processes affecting dense chlorinated solvents and other volatile organic compounds can be evaluated using chlorine isotopes which are fractionated during biodegradation, but are unaffected by dilution and dispersion. MTBE biodegradation can be analyzed with isotopic analysis, the difference between production methane from natural, shallow biodegradation versus leaks from pipelines or production wells can be ascertained. When a compound such as trichloroethene is discovered at a site, compound specific isotopic analysis can help determine whether it is a daughter product of previously spilled tetrachloroethene, or a leak in and of itself.

Site characterization involves understanding groundwater flow and travel times. Isotopic techniques are pivotal in age dating of groundwater, and there are different approaches depending on groundwater's suspected residence times. Relatively young groundwater is often dated by using radionuclides released into the atmosphere during past nuclear weapons testing. For example, tritium (^3H), with a half-life of 12.4 years, with its decay product ^3He, provides a useful tracer of recently recharged groundwater. When calculating groundwater age from tritium, adjustments to $^3H/^3He$ ratios must be made if there is terrigenic helium in the groundwater from the earth's mantle or crust. Tritium to helium-3 ratios are most effective at dating groundwater 0.5 to approximately 40 years old. Another dating technique for modern groundwater 10 years old or younger uses krypton-85, which is produced by nuclear reprocessing and has a similar half-life to tritium, and comparable dating range as well. Nuclear bomb-pulse chlorine-36 is also used to date young groundwater recharged after the 1950s, but in lower, natural concentrations in deep systems can also be used to evaluate submodern groundwater that is 50,000 to a million years old. Methods for dating submodern groundwater (>1,000 years since recharge) include radiocarbon dating (carbon-14). The amount of ^{14}C (half-life 5,730 years) in groundwater can indicate when it was last in contact with the atmosphere, but care must be taken to account for uncertainties due to potential groundwater interaction with carbon from other sources, such as the "dead" carbon in limestones and other carbonate rocks which has no ^{14}C. In optimal conditions ^{14}C can be used to date groundwater about 1,000 to 40,000 years old and can sometimes be used in concert with argon-39 (half-life 269 years). Silicon-32 has the beneficial aspect for groundwater dating of having a half-life of 140 years which allows it to fill a gap between tritium and carbon-14 dating, but its loss and interaction with solid phase silica in an aquifer and analytical difficulties have limited its use. Uranium isotopic ratios are also a useful groundwater dating tool. $^{234}U/^{238}U$ ratios (called uranium isotope disequilibrium) typically increase with groundwater age and can be used to give approximate ages from 10,000 to one million years old. Some isotopes with long half-lives have the potential to date very old groundwater with applications for understanding the isolation of deep contaminant burial, nuclear storage, or deep waste injection. These include iodine-129 (half-life 15.7×10^6 years), krypton-81 (half-life 2.29×10^5 years), and Xeon-139 (half-life 2.165×10^{21} years).

8.7.6 Water Quality Indicators of Groundwater Condition—Microbial testing and Genome Sequencing

Studying subsurface microbiology at contaminated waste sites allows groundwater professionals to calculate the rate of natural attenuation of pollutants, the efficacy of amendments added to groundwater to enhance contaminant breakdown, and the

8.8 Summary

Site characterization involves goal setting and outcome definition, use of noninvasive techniques, followed by strategic application of invasive methods of investigation. In order to collect data for groundwater contamination studies, it is usually necessary to install monitoring wells. Such wells can permit one to measure water levels, collect water samples for analysis, and detect the presence of nonaqueous phase liquids.

Monitoring-well design considers the type and diameter of casing and screen, the material from which the casing and screen is constructed, and whether the well will have an artificial-filter pack or be naturally developed. The annular space between the casing and the borehole must be properly sealed, and the well needs a protective covering. Monitoring wells may be installed by hollow-stem auger drilling, mud-rotary drilling, air-rotary drilling, reverse-rotary drilling, and cable-tool drilling. The equipment used for monitoring-well installation and the material used for the well must be properly decontaminated. Once installed, the well needs to be developed to remove fine material from the area outside the well screen. Water-table wells are installed to monitor the water table and piezometers are used to monitor formations below the water table. Frequently, a water-table well and several piezometers are installed at the same location to form a nest of wells to sample the formations at different depths. Multilevelmonitoring devices may be used to collect samples from very closely-spaced vertical intervals.

There are a number of sampling devices that have been developed to withdraw water samples from monitoring wells. These include bailers, bladder pumps, stator-rotor pumps, piston pumps, and peristaltic pumps. The ability of these devices to collect an unbiased sample varies with the design, technique used, and material from which they are constructed. Prior to sampling a well, it is necessary to purge it to remove stagnant water from the casing. Micropurging techniques result in a water quality sample that is as free of turbidity as possible and at a lower cost than traditional purge and sample techniques due to a shorter time to collect the sample and reduced costs for disposal of contaminated purge water. Soil water must be collected through the use of a suction lysimeter. These are installed in boreholes above the water table. Soil gas vapor can be sampled through active probes that withdraw soil gas samples for analysis or passive devices that sorb soil gas onto activated charcoal devices. Monitoring soil gas can indicate areas where the soil has been contaminated and requires remediation. It can also be used to delineate areas where shallow groundwater is contaminated by volatile organic compounds and where there is a layer of a volatile, nonaqueous phase liquid floating on the top of the capillary zone. Phyto-screening, surface geophysics, and aerial photographic interpretation are other noninvasive or low impact characterization techniques that are appropriate at many sites.

There are a host of chemical and microbial analysis technologies that assist interpretation of the source, movement, and transformation of subsurface contaminants. Differences in source chemistry, generation of daughter compounds, and comparison of compound ratios lend themselves naturally to environmental forensic investigations. Chemical compound transformation, the utilization and uptake of nutrient compounds, varying chemical compound ratios, and changes in subsurface microbial communities all can be indicators of bioremediation and compound attenuation. Geophysics, groundwater dating, and borehole core analysis can define the geologic provenance and flow constraints which affect pollutants.

9

Site Remediation

9.1 Introduction

Since the early 1980s groundwater scientists and engineers have developed a number of techniques for both containing and remediating soil and groundwater contamination. In the United States this has been driven by federal legislation including the Resource and Conservation and Recovery Act (RCRA) and the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA). The Hazardous and Solid Waste Amendments of RCRA address the storage of liquids in underground tanks. Individual states have also passed environmental regulations that may be triggered when property is sold. Regulations associated with these laws dictate when it is necessary to evaluate if a site is contaminated, and if it is, what must be done to remediate the contaminated soil and groundwater. Even in the absence of a specific regulatory requirement, many potential property buyers will require the seller to demonstrate that a property is not contaminated. This may take the form of a Phase I Environmental Study, which involves a detailed review of the historical uses of the property and a review of state records to determine if there is a likelihood of a potentially contaminating activity in the past. This may be followed by a Phase II Environmental Study, where several soil borings are drilled and one or more groundwater monitoring wells are installed. These investigations are for the protection of the buyer and the financing institution because if the property is found to be contaminated after purchase, the new owner would be responsible for some or all of the cleanup costs (Phase III).

In general, remediation of a site must address two issues. If there is an ongoing source of contamination, control of the source will be necessary. There is no point in remediating the environment if new contamination is being released to the soil or groundwater. Examples of sources include landfills, mine tailings piles, leaking underground storage tanks, pipelines, septic tanks, and sewer lines. In addition to primary sources, such as those listed above, there can be secondary sources of contamination due to contaminants which have already been released to the environment. These secondary sources include nonaqueous phase liquids (NAPLS) which may be trapped in the vadose zone, floating on the water table or trapped below the water table. Once the primary source has been removed or isolated, then secondary sources must be identified and isolated. Only after that has occurred is treatment of contaminated soil and groundwater effective.

The final goal of a remediation program for contaminated soils and groundwater is generally subject to approval of a state or federal regulatory agency. In almost all cases it will be impossible to completely remove all contamination so that the site returns to a pristine condition. After all, many contaminated sites have been the locus of industrial activities for decades; indeed, some sites in the eastern United States or in Europe have been used by one industry or another for centuries. In the United States of America, state agencies or the U.S. Environmental Protection Agency may have numerical standards for the soil and groundwater that must be met after site remediation. Similarly, in the European Union, the European Environment Agency (EEA) works together with national agencies on defining what are "good" and "poor" quality water bodies (Water Framework Directive 2000/60/EC of the European Parliament and of the Council). Many other countries have modeled their environmental standards on EPA or European regulations. These standards are generally based on anticipated future land use. Soil remediation standards for future residential land use will be more stringent than those for industrial use. Groundwater standards may be based on drinking water Maximum Contaminant Levels (MCLs).

The application of very stringent standards may result in the expenditure of large amounts of money to reduce extremely small or even nonexistent risks (Viscusi and Hamilton 1996). As much as everyone would like to live in a pristine environment, it simply is not practicable in the post-industrial world. There are limited funds available for environmental cleanup; we should expend those funds in a manner that is most effective in terms of reducing real risks. This has led to the concept of risk based corrective actions (RBCA). Rather than cleaning up all sites to a set standard, a risk assessment of the site is made, and risks to specific receptors are addressed. For example, if the groundwater is saline and not used as a drinking-water source, it may not be really necessary to remove a chlorinated solvent to the drinking-water standard.

Contaminant hydrogeologists in collaboration with engineers, chemists, biologists, modelers, and many other experts have developed some very powerful methods of removing contamination from soil and groundwater. However, these methods are not capable of totally removing all contamination. A zero contamination strategy is not possible, even if we were willing to commit unlimited funds.

In this chapter we will examine a number of source zone and groundwater plume remedial techniques, some proven and some experimental. Table 1 provides an overview of some of the most common technologies and their applicability and development status. There are a few textbooks (e.g., Suthersan et al. 2017) and a number of public domain resources that can guide us in the discussion of these remediation technologies. For instance, the Interstate Technology and Regulatory Council (ITRC) makes available documents ranging from technical overviews and case studies of innovative remediation technologies to technical and regulatory guidance documents for applying cleanup technologies (www.itrcweb.org/guidance). Similarly, the Federal Remediation Technologies Roundtable (FRTR) provides access to a remediation technology screening matrix for screening potentially applicable technologies for a remediation project, including a long list of technology descriptions (www.frtr.gov/scrntools.htm). The National Academies of Sciences, Engineering, and Medicine—National Research Council (NRC) publishes periodic reports on the state-of-the-art in the remediation of contaminated sites (http://www.nap.edu/topic). The Strategic Environmental Research and Development Program (SERDP) is an environmental science and technology program, planned and executed by the U.S. Department

TABLE 9.1 Common and innovative contaminant remediation technologies.

Technology	Application	Development Status
Pump-and-Treat (P&T)	(Source Zone) / Plume / Containment	Established
Physical Containment	Source Zone / Plume	Established
Solidification/Stabilization	Source Zone	Established
Soil Vapor Extraction / Air Sparging	Unsaturated Zone; Source Zone / Plume	Established
Bioremediation and Monitored Natural Attenuation (MNA)	Source Zone / Plume	Innovative / Established
Permeable Reactive Barrier	Source Zone / Plume	Innovative / Established
Chemically Enhanced Flushing	Source Zone	Established
Thermal Treatment	Source Zone / Unsaturated Zone	Innovative / Established
In Situ Oxidation	Source Zone / Plume	Innovative / Established
Phytoremediation	Plume / Unsaturated Zone / Containment	Innovative / Established

Note: The boundary between what is a conventional and innovative technology is fluid.

Source: Modified after NRC 2013.

of Defense (DOD), Department of Energy, and the EPA and others. Together with another U.S. DOD program, the Environmental Security Technology Certification Program (ESTCP), these programs support the development and demonstration of the latest remediation technologies. They also provide access to documents describing innovative, cost-effective, and sustainable environmental cleanup solutions, including for the treatment of DNAPL source zones or groundwater plumes (www.serdp-estcp.org). Funded by the European Union, the EUGRIS (European Groundwater and Contaminated Land Remediation Information System) is an openly available information platform for contaminated land and groundwater information (www.eugris.info/index.asp). While there are many more resources available to students as well as practitioners, one of the largest depositories of information about contaminated site characterization and remediation technologies is maintained by the U.S. EPA (www.clu-in.org). Currently, the website includes information on several hundred field-scale remediation technology demonstration projects.

■ 9.2 Source-Control Measures

9.2.1 Solid Waste

Solid waste may have been buried in an unsecure landfill, placed in an open excavation or old quarry, or simply spread on the land surface. If contaminants continue to be leached from these sources by infiltrating precipitation, or even groundwater if the solid wastes have been buried below the water table, then a source-control measure is necessary before groundwater remediation is attempted. If the source continues to leach contaminants, then groundwater remediation may be futile.

Source-control measures include physical removal of the waste and transportation to a secure landfill or incinerator, construction of impermeable covers or low-permeability caps to eliminate or minimize infiltration of precipitation, and construction of physical barriers around the waste source.

9.2.2 Removal and Disposal

If the source is removed, then wastes can no longer migrate from it. Solid waste that has been spread on the land surface can easily be removed by conventional earthmoving equipment. Waste that has been buried in a landfill can also be exhumed and transported to a secure landfill. A hazardous-waste landfill was operated near Wilsonville, Illinois, USA, from 1976 to 1981. Hazardous wastes, including liquids, were buried in drums that were placed in 26 trenches, each approximately 3.3 m to 6.5 m (10 to 20 ft) deep, 15 to 30 m (50 to 100 ft) wide, and 53 m to 122 m (175 to 400 ft) long. In 1981, it was found that hazardous wastes had migrated up to 16.7 m (50 ft) from the trenches over a 3-year period, a rate 100 to 1000 times greater than predicted prior to construction of the landfill. Following a court order, the site owner exhumed and removed all the drums and transported them to a more secure landfill. The process took 4 years and many millions of dollars (Herzog et al. 1989).

Excavation and removal of hazardous materials must be done in a manner that protects the health and safety of workers and the public. The materials may be hazardous if one comes into contact with them, they give off toxic or dangerous vapors, or if ingestion of these materials would be harmful. The risk of moving material as opposed to leaving it in place must always be evaluated prior to a removal action.

Furthermore, the final disposition must be environmentally sound. In at least one case, spent solvents were moved from an abandoned hazardous-waste site to a solvent-recycling facility. The latter facility eventually went bankrupt and became a hazardous-waste site itself. Under CERCLA, the courts have found that the generator of hazardous wastes is responsible for their cleanup and disposal costs if the disposal-site operator becomes bankrupt. In this case, the generator had to pay twice for the disposal of wastes. This policy is known as "cradle-to-grave" and is designed to ensure that hazardous waste is controlled from the time it is generated until its ultimate disposal. The EPA defines hazardous waste as "waste with properties that make it dangerous or potentially harmful to human health or the environment" (U.S. EPA 2016). In regulatory terms, an RCRA hazardous waste falls into two categories: (1) waste specifically listed by EPA and (2) characteristic waste which exhibits one or more of the following: ignitability, corrosivity, reactivity, or toxicity. These four waste characteristics are communicated in many different ways, including Material Safety Data Sheets (MSDS) or by hazard labels. For instance, the NFPA 704 chemical hazard label standard uses a diamond-shaped diagram of symbols and numbers to indicate the degree of hazard associated with a particular chemical or material (Figure 9.1). You probably have seen this or similar signs posted in laboratories or other places where potentially hazardous materials are being stored. In any given state, the EPA or the state hazardous waste regulatory agency enforces hazardous waste laws and most universities have hazardous waste offices to ensure compliance with those laws.

FIGURE 9.1 The NFPA 704 chemical hazard label. Each quadrant is labeled with its respective color and hazard.

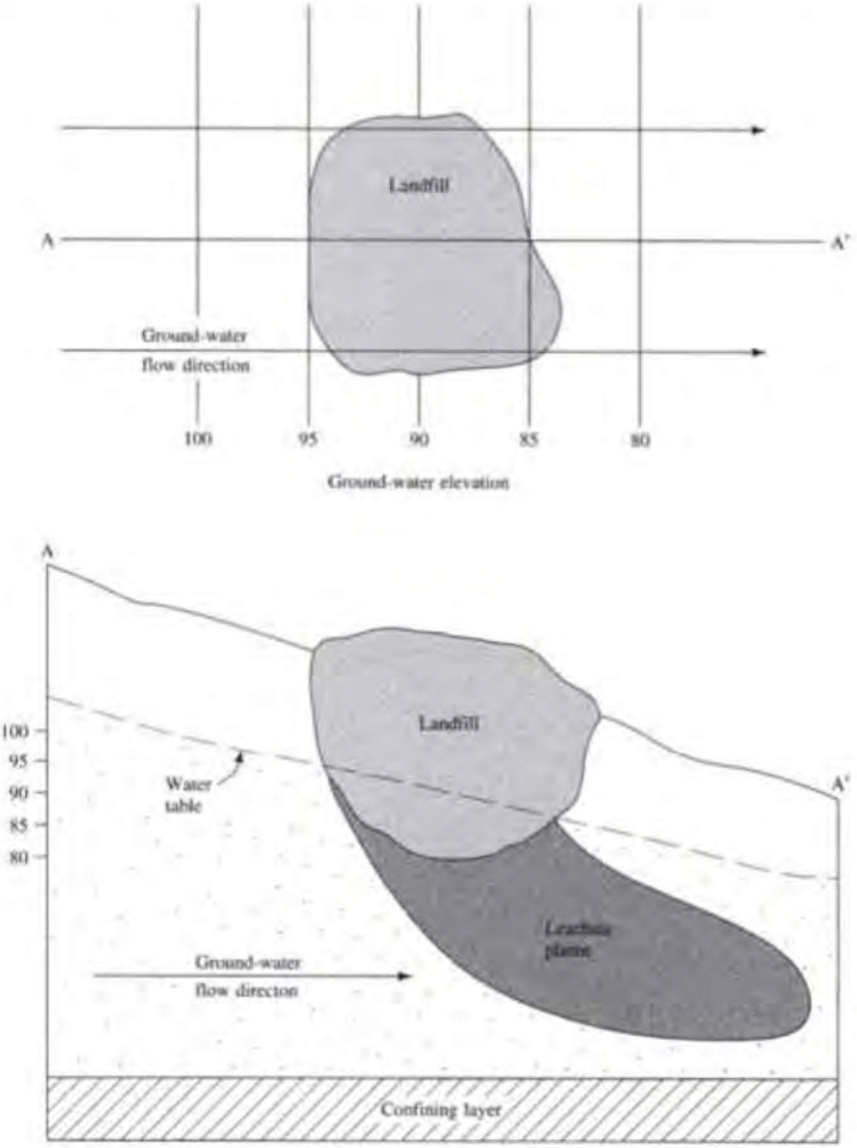
Soil contaminated with organic compounds may be remediated by excavation and incineration. This is a technique that has been proposed for highly refractory organic compounds, such as PCBs and some pesticides. The organic matter of the soil is incinerated while a supplemental fuel is burned in the incinerator. Incineration converts the waste into ash, flue gas, and heat. While the heat can be utilized for beneficial purposes, there is concern about toxic compounds that might accumulate in the ash and gaseous emissions of the incinerator plant. The appropriate disposal of the ash and the filtration of the flue gas add significant cost to the waste incineration and make this process expensive. Compounds with a high BTU (heat) value, such as hydrocarbons, can also be incinerated. This is less costly, since supplemental fuel is not needed. However, permits are needed for incineration, and these may be difficult to obtain from state and local authorities.

9.2.3 Containment

If the waste cannot economically or technically be excavated, then it may be possible to contain it. If the waste is below the water table, flowing groundwater can pass through it and create leachate as illustrated in Figure 9.2a. Such buried waste can be surrounded by a **groundwater cutoff wall**. The purpose of the groundwater cutoff wall is to divert groundwater flow from passing through the waste so that it cannot form leachate (Lynch et al. 1984; Need and Costello 1984). The cutoff wall needs to be deep enough to key into an impermeable layer so that groundwater cannot pass under the wall, which is referred to as encapsulation. Note that the term encapsulation is not only used to describe the isolation of an area of waste, but is used also to describe the different measure of surrounding an individual container with impermeable material.

There are several ways that cutoff walls can be used (U.S. EPA 1998). The wall can extend all around the waste (Figure 9.2b). If this is done, the groundwater will flow around the wall and be diverted from the waste. The water table will rise on the upgradient

FIGURE 9.2a Top view and cross section of a landfill that was constructed with an excavation that extends below the water table. Groundwater can flow through the waste and create leachate.

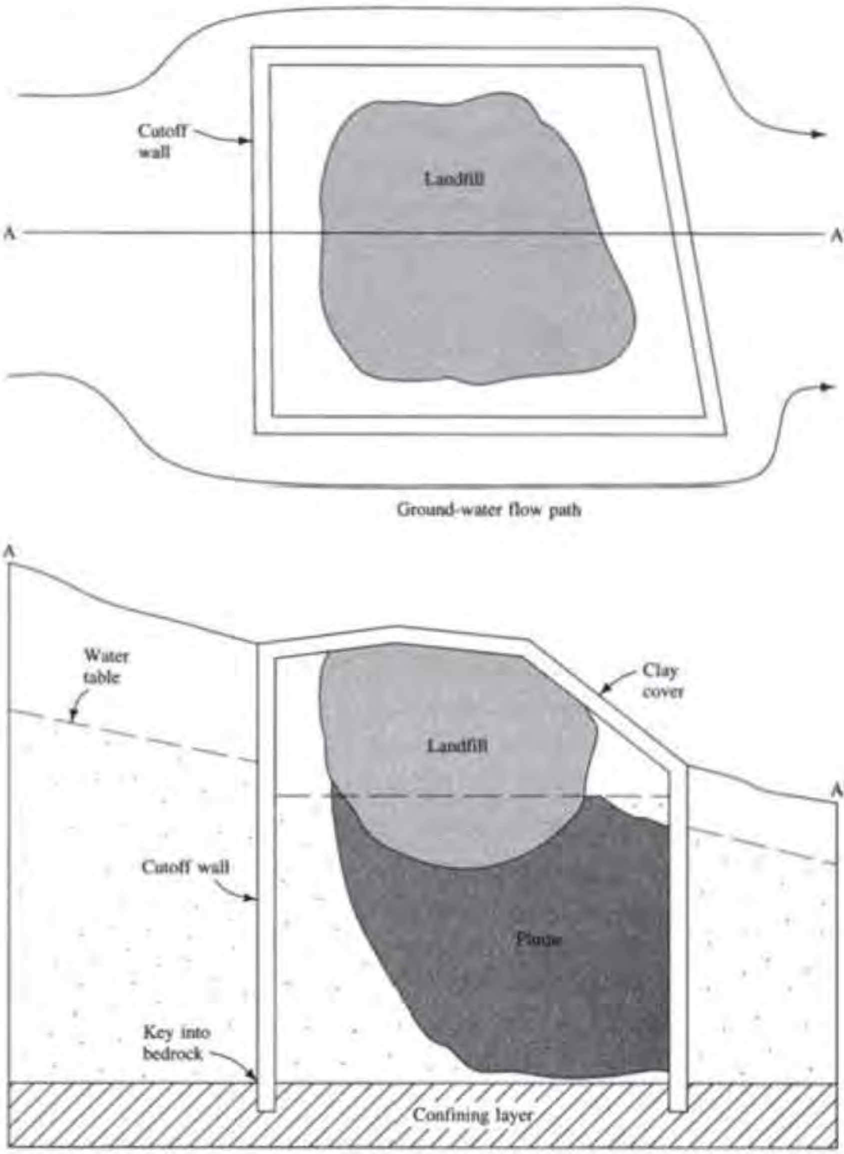


wall and fall on the downgradient wall. If there is no recharge or flow through the cutoff walls, the water table within the cutoff walls will be flat. However, there is generally leakage through the cover or cutoff walls, so some extraction wells will be needed for added hydraulic control within the cutoff walls to prevent build-up of water within walls.

If the cutoff walls are extended far enough to surround both the waste body and the plume of contamination, then remediation may proceed without worry that it will spread further. One of the problems that have arisen with the remediation of groundwater is that the plume may spread rapidly, whereas legal action to assess blame for the plume proceeds through the courts with glacial speed. If a cutoff wall is installed as an emergency action, then the plume can wait until the courts have spoken.

Cutoff walls have also been used to stop the spread of a contaminant plume. At the Rocky Mountain Arsenal near Denver, Colorado, USA, a cutoff wall was constructed

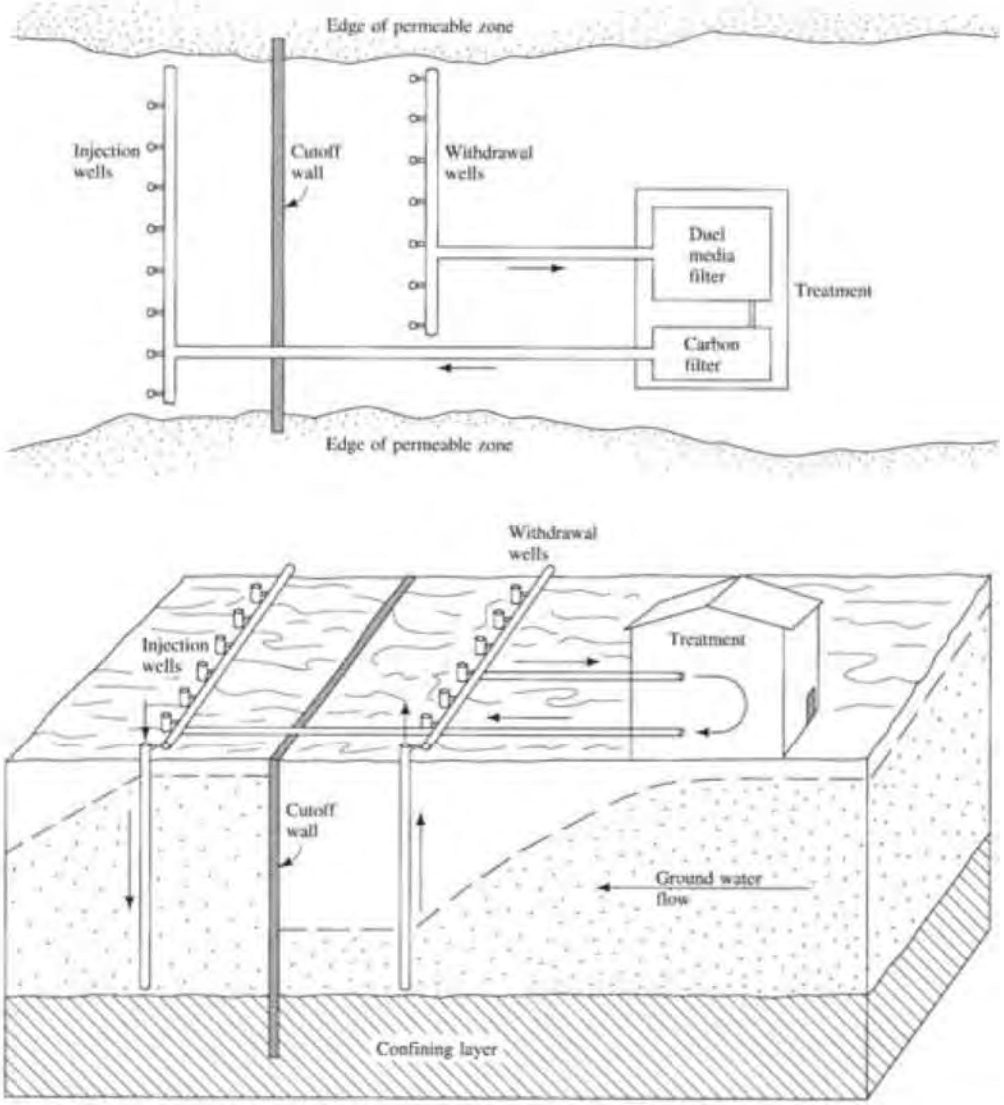
FIGURE 9.2b Top and side view of a cutoff wall that completely surrounds the landfill in (a), opposite page. Cutoff wall is keyed into underlying low-permeability formation.



across a bedrock valley containing higher-permeability, unconsolidated deposits that acted as a pathway for a contaminant plume. The contaminated water is pumped from the upgradient side of the cutoff wall, treated to remove the contamination, and injected into the aquifer on the downgradient side of the cutoff wall (U.S. EPA 1998). This system is illustrated in Figure 9.3.

A number of different types of materials have been suggested for use in cutoff walls (Pearlman 1999). Most are constructed of soil-bentonite slurries, but concrete and concrete/polymer mixtures are also used particularly in regions of topographic relief. A trench is excavated with an excavator or backhoe. The trench is held open by a slurry of bentonite and water. The slurry acts in the same manner as the drilling mud that holds open a borehole. The bentonite slurry penetrates into the more permeable formations and forms a low-permeability filter cake. As the working end of the trench

FIGURE 9.3 Cutoff wall used with extraction and injection wells at the Rocky Mountain Arsenal, Denver, Colorado, to isolate and treat a plume of contaminated groundwater.



is built around the site, the opposite end of the trench is back-filled with a soil-bentonite slurry. The soil-bentonite slurry has a very low permeability and minimizes the movement of most groundwater through it. The trench is typically 1 m (2 to 3 ft) wide and can be up to 18.3 m (60 ft) deep if excavated with a backhoe or up to 36.5 m (120 ft) deep if dug with a clamshell shovel (Need and Costello 1984). While expensive, technology to install cutoff walls as deep as 122 m (400 ft) is available (Valkenburg 1991). Preconstruction design studies are needed to determine if the waste that is to be contained is compatible with the bentonite-soil slurry.

A grout curtain may also be constructed as a cutoff barrier. Grout is injected into the earth through a borehole. The grout is liquid when injected but eventually hardens into an impermeable material. This approach was used to contain radioactive water at the Fukushima nuclear power plant disaster site in Japan, according to the company in charge for the site remediation (www.tepco.co.jp). Other construction methods include steel-sheet piling, bored pile walls and, as temporary solution, artificial ground freezing. The selection of a cut-off barrier construction method will depend on the desired depth of wall, ground conditions, and geometry of wall.

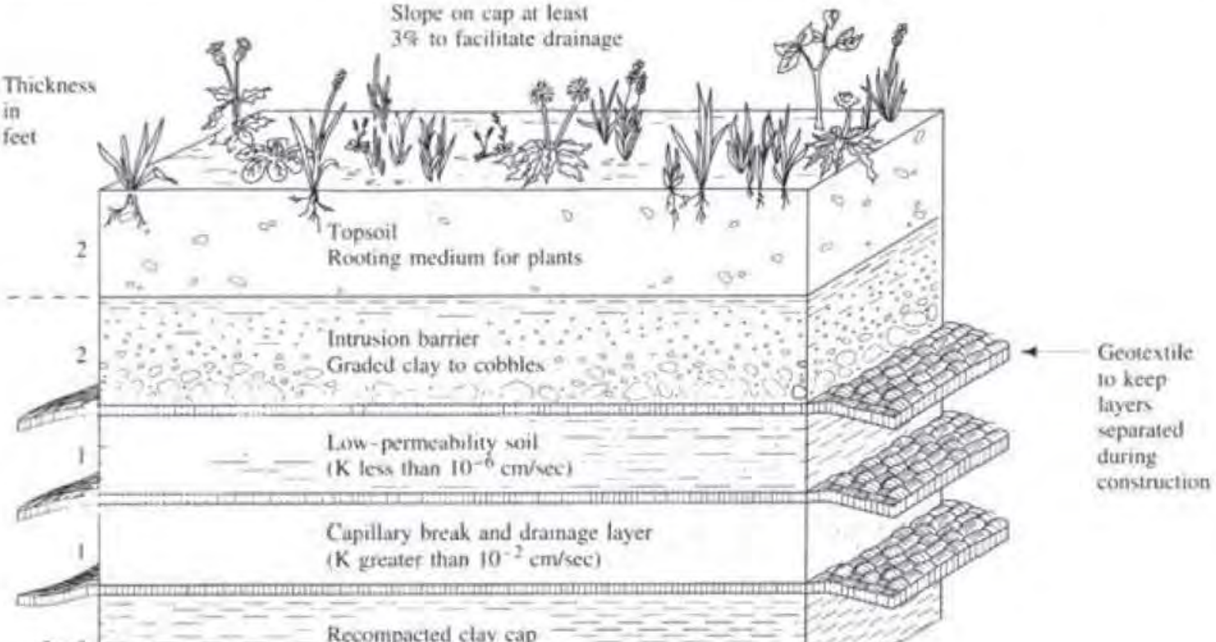
If contaminated material can be immobilized or its solubility reduced through a chemical reaction, this process is called stabilization. Similarly, if the contaminated material can be encapsulated to form a solid and to restrict its migration by decreasing the surface area exposed to leaching, that process is referred to as solidification. **Solidification/Stabilization** is an established technology that has been used for decades to address a variety of *in situ* and *ex situ* solid and liquid wastes. Typically, the contaminated material is treated with an inorganic or organic binder, such as cement, fly ash, lime, soluble silicates or asphalt, epoxide, polyesters, and polyethylene (U.S. EPA 2000).

In most cases it will also be necessary to construct a cover over the waste material to prevent the infiltration of precipitation. If the waste material is above the water table, a cover without a slurry wall might be all that is needed. For a waste material buried below the water table, a low-permeability cover is needed in association with a slurry wall. In the absence of a cover, the infiltrating water will fill the area within the slurry wall like a bathtub.

Covers may be constructed of native soils, synthetic membranes, or a combination of both. Covers are typically sloped in order to promote runoff of precipitation. It may even be necessary to bring in fill material to create the necessary elevation at the center of the cover to form the needed slope.

A multilayer cover constructed of natural materials might have the following elements, starting from the surface (Figure 9.4): (1) 0.6 m (2 ft) of topsoil as a rooting medium for vegetation with shallow roots, such as grass or crown vetch, which is

FIGURE 9.4 Typical design of a multilayer cap for a landfill that is constructed of natural soil materials.



needed to prevent erosion; (2) a 0.6 m (2 ft) thick compacted layer of cobbles mixed with clay to stop burrowing animals from breaching the cap; (3) a 0.3 m (1 ft) thick low-permeability zone to separate the cobble layer from the next-lower zone; (4) a 0.3 m (1 ft) thick layer of very permeable sand, which acts as a capillary break to the movement of soil moisture and provides for lateral drainage of any infiltrating precipitation; and (5) a bottom layer that consists of 0.6 to 1 m (2 to 3 ft) of recompacted clay with a maximum permeability less than 10^{-7} cm/sec (8.5×10^{3} ft/d) to act as a final barrier to groundwater recharge. Geotextile fabric would be needed between several of the layers to keep the materials from mixing during construction and to distribute the stresses evenly. Figure 9.4 shows the details of this design. Erosion of the soil and penetration of the cover by tree roots are the main concerns for the long-term integrity of this design.

Synthetic geomembranes can also be used in cover designs as low-permeability layers. One advantage of using native soil materials is that their long-term performance is assured, whereas the long-term behavior of plastic membranes, and those made of other materials has not been tested for all types of soil, climatic, and contaminant mixture scenarios. However, for many applications, plastic membrane covers are suitable. They can easily be installed so that monitoring and extraction wells extend through the cap.

Infiltration of precipitation into the ground can also be reduced by paving the surface with a material such as asphalt. However, an asphalt seal is more permeable than a multilayer cover and would require extensive maintenance to seal cracks that form. Diversion ditches and drains might be used to prevent surface runoff from entering an area where it can infiltrate into the soil and come into contact with buried waste material.

There are alternative cover designs that are increasingly being used for waste disposal sites and hazardous waste landfills. For instance, the evapotranspiration (ET) cover system relies on the properties of one or more vegetated soil layers to store water until it is either transpired through vegetation or evaporated from the soil surface (e.g., Hauser et al. 2001). Compared to conventional land fill covers, ET cover systems are less costly to construct. However, ET cover systems are mostly limited to areas that have arid or semi-arid climates, such as the southwestern United States (U.S. EPA 2003; 2011).

9.2.4 Hydrodynamic Isolation

Hydraulic controls can also be used to isolate a zone where the groundwater has been contaminated. An extraction well positioned at the leading edge of a contaminant plume can be used to stabilize the position of the plume or contain it (Figure 9.5). The plume-stabilization well will pump contaminated water, which may require treatment before disposal. It will prevent the encroachment of the plume of contamination to uncontaminated parts of the aquifer. With the contamination thus isolated, work on source control and other remediation measures can progress at the most expedient pace.

The downgradient limit of the capture zone is called the stagnation point. Figure 9.6 shows a water table profile along the y-axis. It can be seen that the stagnation point forms a groundwater divide between flow toward the well and flow in the regional direction. The stagnation point and the capture zone are also shown for an LNAPL spill in Figure 9.7. Note that there is a maximum quantity of water that can be pumped from a single extraction well. If the plume is wider than the capture zone developed by the maximum pumping rate, then multiple extraction wells are needed. One concern with multiple extraction wells is that their capture zones must overlap,

FIGURE 9.5 Plume-stabilization well used to isolate plume of contaminated groundwater.

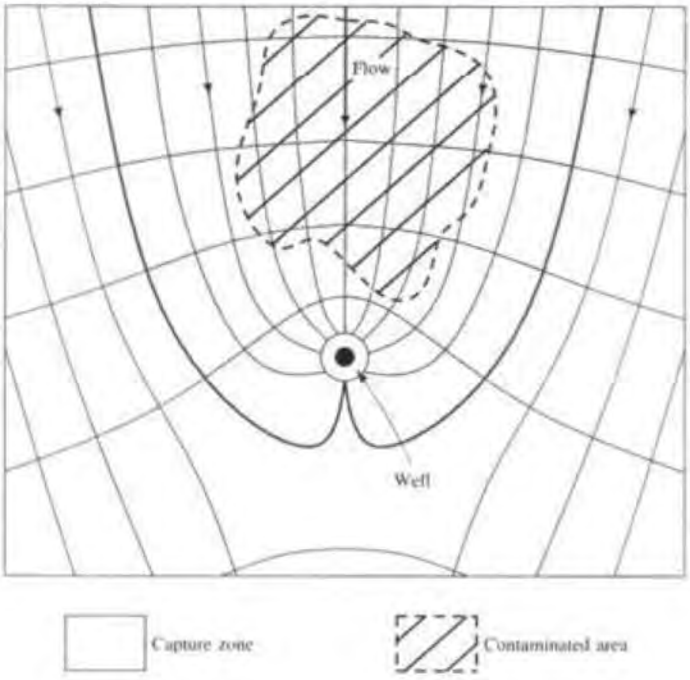
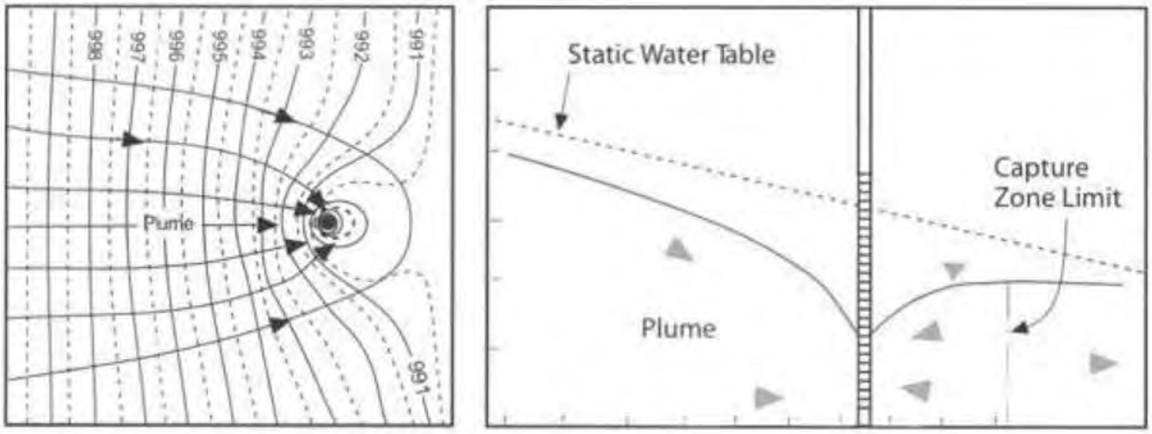


FIGURE 9.6 Example of plume stabilization by a well which is used to hydraulically contain a plume of contaminated groundwater. Shown are plan view and cross sections.

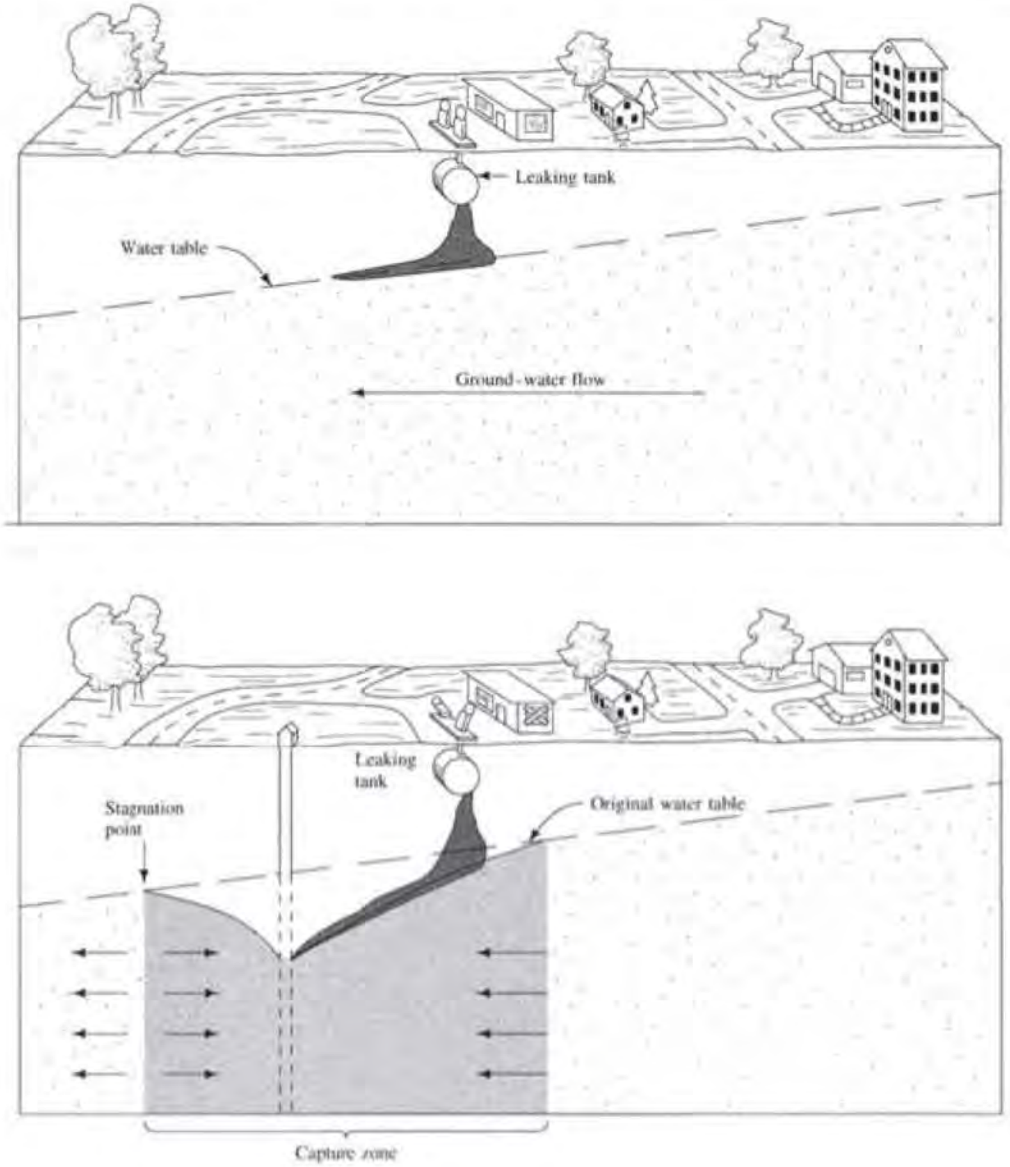


Source: After Cohen et al. 1993; as cited in U.S. EPA 1995, Report EPA/625/R-95/005.

or groundwater flow can pass between them. These considerations illustrate why contaminant hydrogeologists regularly rely on groundwater models as an important aide in designing remediation systems.

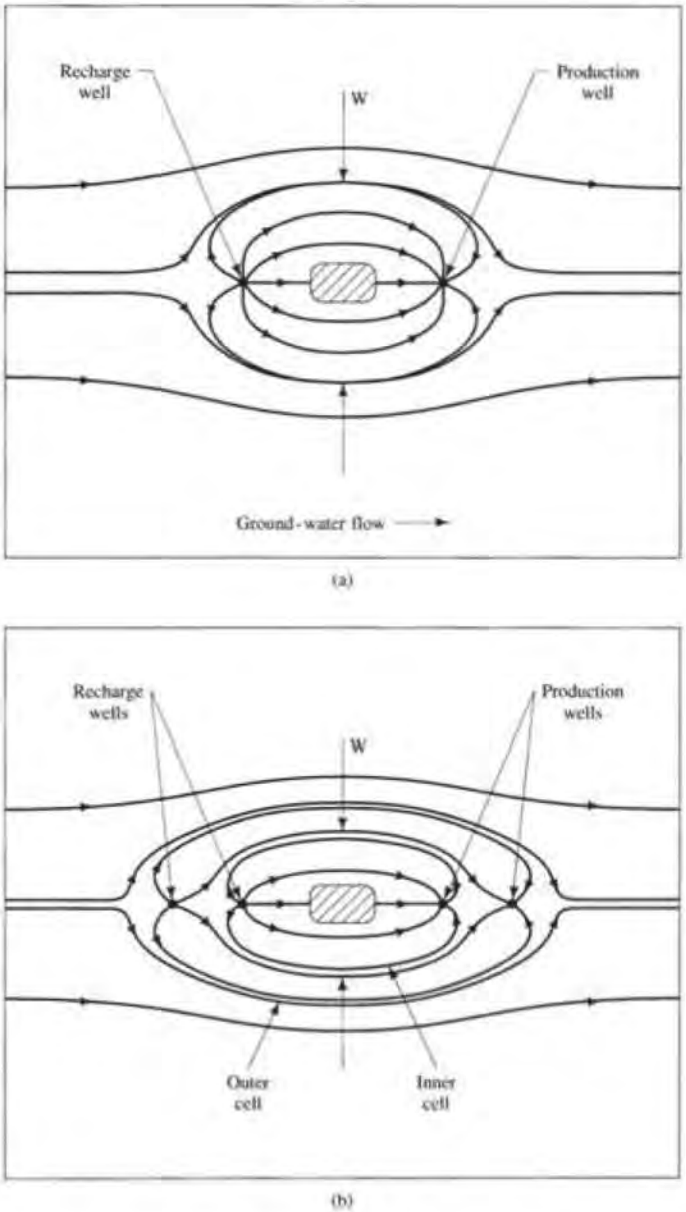
Wilson (1984) described the use of a pair of injection and withdrawal wells to create a hydraulic isolation zone around a plume of gasoline contamination. The withdrawal well draws contaminated water to it; the water is then reinjected into the ground upgradient of the position of the plume (Figure 9.8a). The withdrawn water may be treated prior to injection, or nutrients can be added to promote bioremediation. In addition, treatment systems may need periodic maintenance necessitating a shutdown.

FIGURE 9.7 Cross section along the *x* axis showing the cone of depression for a single extraction well superimposed on the regional water table.



With a reinjection system the untreated water can still be injected and the downgradient plume-stabilization well can be kept pumping. Otherwise, if the plume-stabilization well is shut down, the plume might be able to spread beyond its hydraulic boundary. Care must be exercised to minimize smearing of LNAPLs by reducing rigorous pumping that results in great fluctuations of the water table. Wilson (1984) also described a double-cell hydraulic containment system with two pairs of injection and production wells, as shown in Figure 9.8b. This system provides further isolation of the plume and also creates a smaller inner cell so that the production well that is pumping contamination will pump a smaller volume of water, which will lower treatment costs. With two injection and pumping wells, there is a possibility of shutting down one well periodically for maintenance and still having the system operational.

FIGURE 9.8 Plan view of (a) single-cell and (b) double-cell hydraulic containment of contaminated groundwater.



Source: J. L. Wilson. 1984. Proceedings of the Fourth National Symposium and Exposition on Aquifer Restoration and Ground Water Monitoring, 65–70. National Water Well Association. Used with permission.

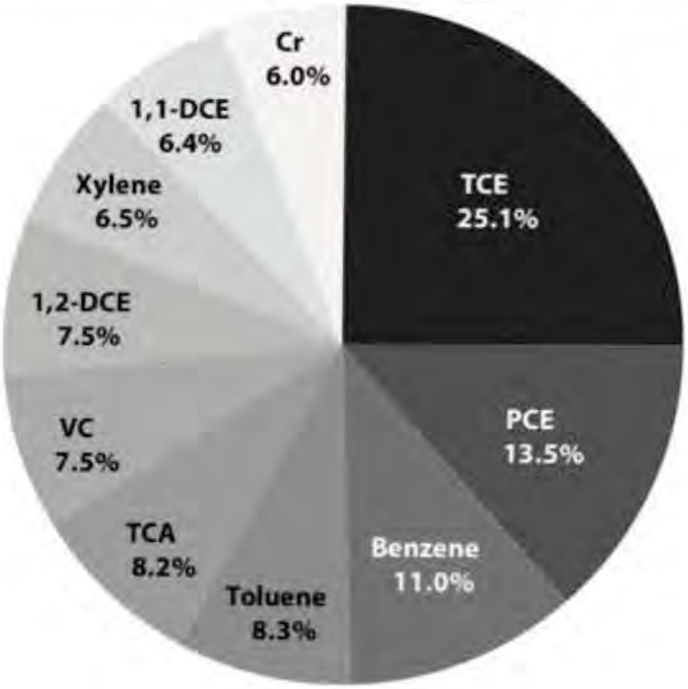
■ 9.3 Pump-and-Treat Systems

9.3.1 Overview

For a long time, almost all groundwater remediation was based on extraction wells or drains that were usually accompanied by treatment of the extracted water before discharge (Mackay and Cherry 1989). The extraction of groundwater that contains dissolved inorganic and organic chemicals removes the contaminants from the subsurface so that the contaminated groundwater can be treated at the surface. This remediation approach is known as Pump-and-Treat (P&T). The advantage of the P&T method is that conventional methods of wastewater treatment can be employed. Pump-and-treat was the sole remedy at 56% (485 of 877 sites) of National Priority List (NPL) sites in the United States between fiscal years 1982 and 2005, representing the most common groundwater remedial action during that period (U.S. EPA 2007). Figure 9.9 provides an overview of the 10 most frequently treated contaminants using P&T technology. P&T systems also are frequently used to treat metals and metalloids, including chromium (U.S. EPA 2007). There are, however, a number of disadvantages that limit the usefulness of this technology to emergency responses, plume containment in combination with source-control measures, or treatment of highly water soluble compounds. Since the early 1990s many highly efficient groundwater treatment technologies have been devised and tested so that contaminated site managers now have alternatives to the P&T technologies. Not surprisingly, by 2011 only 22% of groundwater remedies at NPL sites were P&T based (U.S. EPA 2013).

Depending on the efficacy of treatment and regulatory requirements, the treated water can be discharged to a receiving water body, passed to a publicly owned wastewater treatment plant for further treatment and dilution, or reinjected into the ground. Often the disposal of the treated wastewater requires state and local permits or regulatory approval. Discharge to a publicly owned wastewater-treatment plant may require local permits for industrial discharge and there might be pretreatment standards. Water

FIGURE 9.9 Contaminants treated most commonly by pump-and-treat systems: trichloroethene (TCE); tetrachloroethene (PCE); 1,1,1-trichloroethane (TCA); 1,2-dichloroethene (1,2-DCE); 1,1-dichloroethene (1,1-DCE), vinyl chloride (VC), and chromium (Cr).



Source: U.S. EPA 2007.

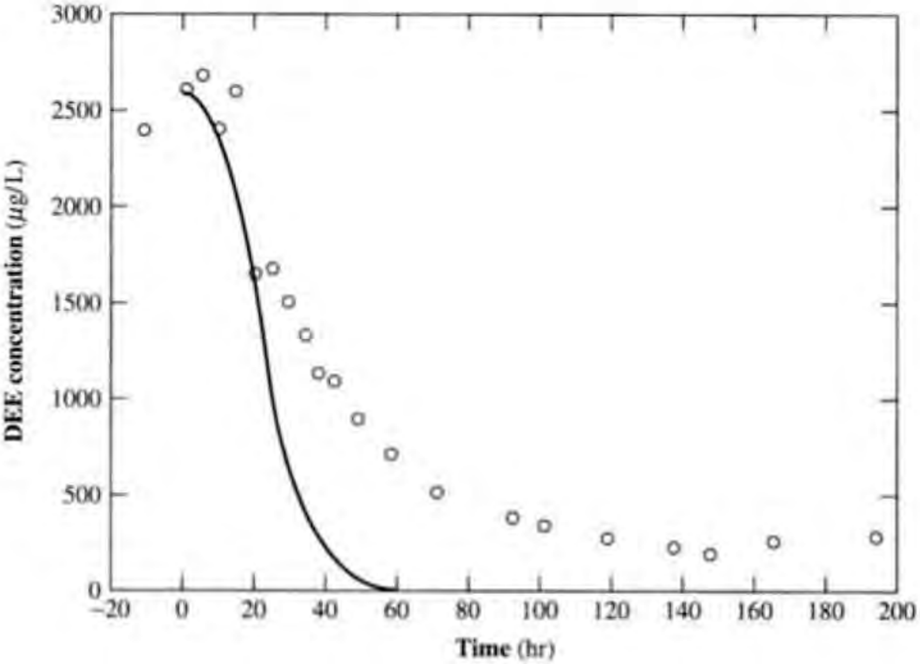
discharged to a surface-water body in the United States requires state permits, including a National Pollutant Discharge Elimination System (NPDES) permit. Many states provinces, and regions require a permit to inject water into the ground and there may be concentration limits specified as a part of the permit. If there are NAPLs present, the situation is much more complex than if all contaminants are in a dissolved form. As long as an NAPL is present, it will partition between the NAPL phase and the dissolved phase. Thus, as contaminated water is withdrawn from the aquifer for treatment, the clean water that is drawn into the aquifer eventually becomes contaminated with pollutants partitioning from the remaining NAPL. If some of the NAPL is mobile, it may be captured by pumping. LNAPLs that are floating on the water table are relatively easy to locate and remove if the LNAPL has not been smeared vertically. However, DNAPLs that sink to the bottom of the aquifer are very difficult even to locate, much less recover (Mackay and Cherry 1989; Freeze and Cherry 1989). Because considerable amounts of residual NAPL will remain even if the mobile NAPL is removed, a great many years may be required for pump-and-treat systems to remove all the residual NAPL by partitioning into the recoverable dissolved phase. In the case of contamination by DNAPLs especially in fractured rock aquifers, it may be very difficult or impossible to remediate a contaminated aquifer (Mackay and Cherry 1989; Freeze and Cherry 1989; National Academies of Sciences, Engineering, and Medicine 2015).

If the dissolved phase sorbs onto the mineral matter of the soil, that phase may desorb as the contaminated water is flushed from the pores. The greater the distribution coefficient, the more slowly the sorbed phase will be released and the longer it will take to remediate the aquifer. The kinetics of desorption dictate that many pore volumes of uncontaminated water might be needed to remove completely the sorbed phase of both organic and inorganic contaminants. Whiffin and Bahr (1984) noted that the observed rate at which organic compounds desorbed from an aquifer was slower than the rate predicted by transport equations that assumed equilibrium conditions between the sorbed phase and the dissolved phase (Figure 9.10). The advection-dispersion equation results were initially fairly accurate; however, when the concentration dropped to about half the initial concentration, the actual rate of removal was slower than the predicted rate.

The discrepancy between the Whiffin and Bahr (1984) model and the observations in the field are related to contaminant residence time in the subsurface and diffusion transport processes. Hence, in heterogeneous media, some contaminants can be sequestered for long periods of time, despite active pumping. Contaminants that have been in the ground for a long period of time have been able to diffuse into the less permeable zones of porous media aquifers or into the bedrock matrix of fractured rock aquifers. Pump-and-treat systems are inefficient in removing these contaminants, because the majority of the water being removed by pumping will come from the most permeable zones of the aquifer. In alternating layers of sand and clay, the contaminated water will penetrate the fine clay, which has very limited permeability, from the highly permeable sands over time. Some of the contamination will remain in the dissolved phase, some will partition onto the surface of the clay lens and associated soil organic carbon and some will diffuse into the clay lens. The fine sediment will have a larger surface area per unit volume of the aquifer than the coarse sediment and thus will sorb more contamination.

These mass transport limitations have been illustrated by Mackay and Cherry (1989) (Figure 9.11). Figure 9.11a shows contamination residing in homogenous aquifer

FIGURE 9.10 Measured desorption values for diethyl ether for water pumped from a purge well (open circles) versus calculated desorption curve based on advection-dispersion equation (solid line).



Source: R. B. Whiffin and J. M. Bahr. 1984. Proceedings of the Fourth National Symposium and Exposition on Aquifer Restoration and Ground Water Monitoring, 75–81. National Water Well Association. Used with permission.

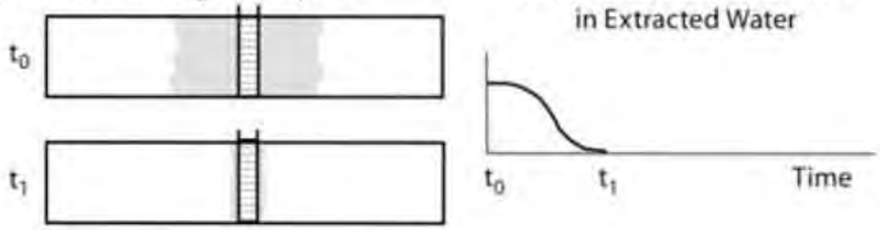
composed of uniform sand. During the time interval t_0 to t_1, the contamination is effectively flushed out. However, if the porous media is heterogeneous and the aquifer consists of sand with an interbedded clay lens, the concentration in the effluent from the extraction well is still elevated at t_1 (Figure 9.11b). Water removed by pumping will come primarily from the sandy material. The contaminated water in the pores of sand will be fairly quickly removed; perhaps only a few pore volumes of water will need to be flushed through to accomplish this. Contaminants sorbed onto the sand grains will be removed by partitioning into the clean water that then occupies the pores in the coarse sand layers.

Meanwhile, the contaminated water occupying the pores of the clay lens will be flushed from this layer very slowly. It will take the movement of many pore volumes of water through the sand to flush just a few pore volumes of water through the much less permeable clay layer. Hence, it will take much longer to remove the contaminants that are desorbing from the fine sediments after the contaminated pore water is removed from the sand.

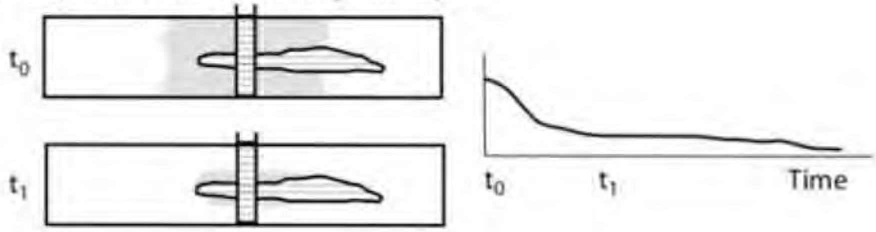
There will be an initial rapid decline in the concentration of contaminants in the water being removed by a pump-and-treat system. This decline represents the removal of the contaminated water contained in the larger pores of the aquifer. Initially, when the larger pores in the sandy material are being flushed, the drop in concentration will be rapid. Flushing the much smaller pores in the clay will take much more time and, the rate at which the concentration declines will decrease. The concentration will eventually approach somewhat constant value, which represents a steady state condition where the rate at which the contaminants are being removed by the pump-and-treat

FIGURE 9.11 Hypothetical examples of contaminant removal during pump-and-treat treatment. Gray areas indicate sorbed and dissolved contaminants (uniform initial distribution). Lined shapes indicate clay lens. Black areas indicate NAPL.

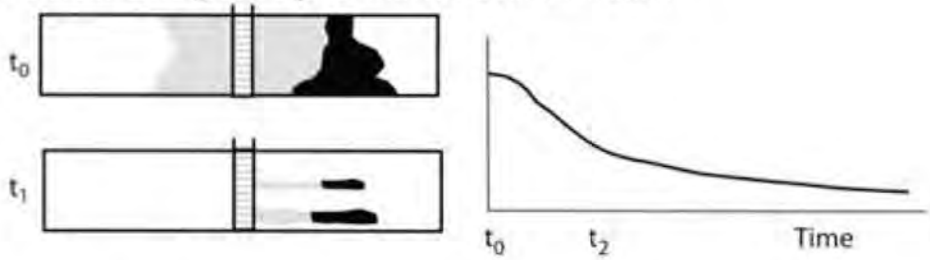
(a) Uniform sand-gravel aquifer



(b) Clay lens in uniform sand-gravel aquifer



(c) Uniform sand-gravel aquifer with NAPL contamination

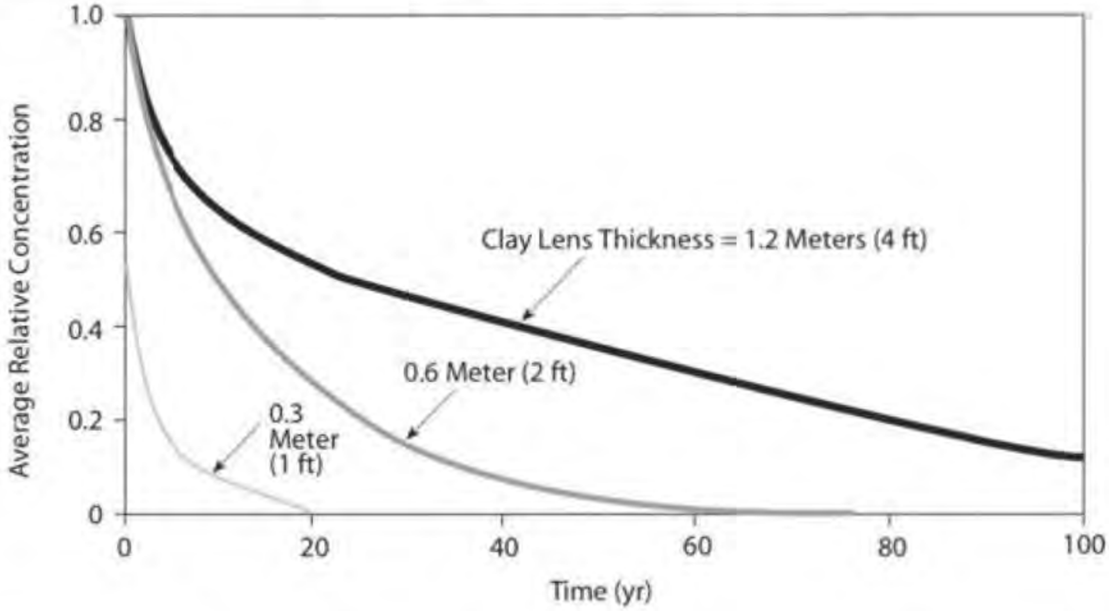


Source: Modified after Mackay and Cherry 1989.

system is equal to the rate at which they are being released into the groundwater by diffusion desorption and/or partitioning from residual NAPLs (Figure 9.11c). The resulting long period of slow release of contaminants to the groundwater is called the **tailing** phase of the remediation.

During the tailing phase in the remediation process contaminant mass is still being removed from the aquifer, but the groundwater is not becoming any cleaner. The concentration at which this occurs may be higher than the cleanup goals for the remediation. It may take many years of pumping at this stage to reduce the amount of sorbed contaminants and/or the residual NAPLs sufficiently for the groundwater quality to improve to a point where it meets cleanup goals. Figure 9.12 depicts how the slow, diffusion-controlled release of contamination from material of low hydraulic permeability (clay) can determine the length of the remediation period. For instance, it would take about 10 years to reduce the TCE concentration by 90% if the clay lens is 0.3 m (1 ft) thick. The time increases to almost 40 years for a lens 0.6 m (2 ft) thick and to over

FIGURE 9.12 The effect of matrix diffusion on the average relative trichloroethene (TCE) concentrations in clay lenses of varying thickness as a function of time.



Source: U.S. EPA 1996.

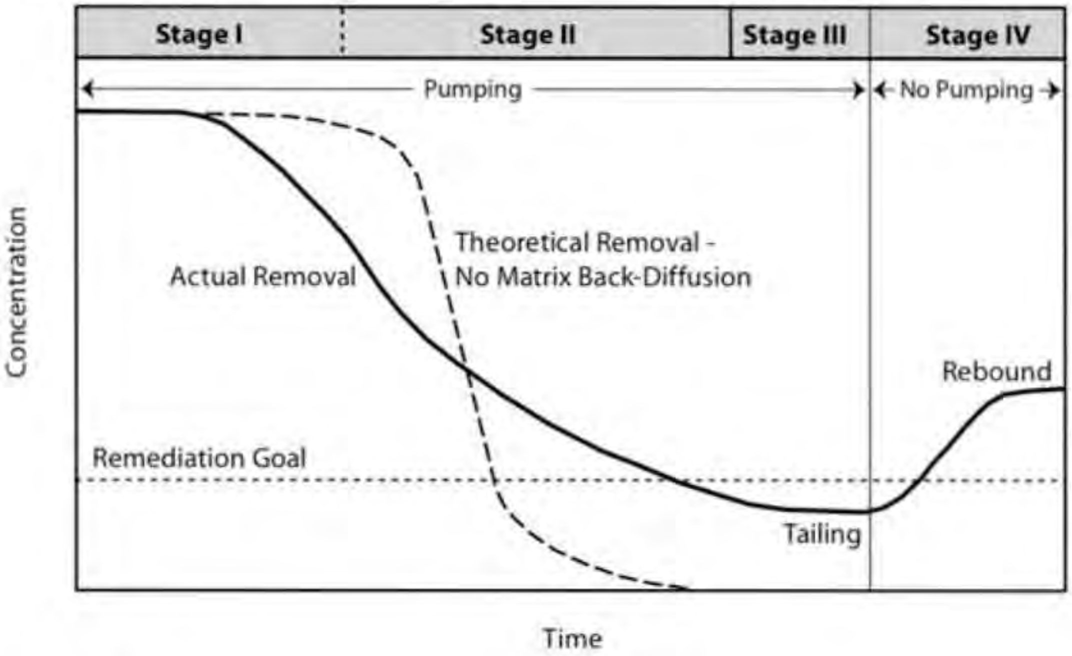
100 years for a lens 1.2 m (4 ft) in thickness. These simulations show that it may take decades or longer to significantly lower the contaminant concentration in clay lenses.

A study of pump-and-treat cleanup at 16 sites in the United States where the groundwater was contaminated with organics revealed that if the initial concentration of contamination was high (>1000 μg/L), pumping could achieve reductions of contaminant concentrations of 90 to 99% before leveling occurred. At sites where the initial concentration was less than 1000 μg/L, leveling occurred before a 90% reduction was accomplished (Doty and Travis 1991). Moreover, if remediation is halted before the sorbed phase is completely removed, the dissolved concentration will eventually **rebound** and rise above the level detected at the end of the remedial period as additional material desorbs to come to equilibrium with the dissolved phase. Typically, the rebound of the dissolved contaminant concentration is quick, i.e., can occur within a few days after the pumping ceased.

The effects of rebound and tailing on the progress of P&T treatment are illustrated in Figure 9.13. It must be noted that these effects are not solely limited to P&T systems, but also affect other, more innovative groundwater treatment technologies that rely on chemically-enhanced flushing processes to remove contamination from low-permeability material.

Figure 9.13 illustrates the multiple stages in remediation of a contaminated aquifer or soil. Early during the treatment (Stage I), there is rapid removal of contaminant mass and concentrations drop quickly. Stage I transitions into Stage II which represents the diffusion-controlled period as the concentration graph attains an asymptotic shape. During the tailing stage (Stage III), the rate of mass removal slows because the site geology controls the rate at which the remaining contamination is released. The impact of matrix diffusion is illustrated by the dashed line curve, which shows the theoretical removal expected in

FIGURE 9.13 Stages in the remediation of a contaminated aquifer or soil.



Source: Modified after U.S. EPA 1996.

the absence of diffusion from low-permeability domains into higher permeable zones. Remediation efforts continue until a pre-determined clean up goal has been reached. In some cases, that remediation goal may be higher than the pollutant specific standard, like the maximum contaminant level (MCL) defined by the U.S. EPA. When at one point the pumping stops, it is likely that the slow, diffusion-controlled release of contaminants from low-permeability domains results in an increase in the dissolved phase concentration. This is Stage IV, the rebound stage. Should the rebound result in groundwater concentrations higher than the cleanup standard, remediation must continue. Under these circumstances, it may be necessary to periodically turn on the pump(s) until the residual concentration drops beneath the remediation goal again. Such a treatment scheme is known as **pulsed pumping** (U.S. EPA 1996). Another option is to vary the pumping rates or turn injection wells into extraction wells and vise-versa. This **adaptive pumping** approach limits the development of stagnation zones, which are parts of the aquifer that are not, or only minimally, flushed if the extraction/injection scheme was static.

Figure 9.13 illustrates an aquifer where the contaminant is in the dissolved phase or is sorbed onto soil particles. If there is an undissolved phase (DNAPL) present, then the release of contaminant into the flushing water will be controlled by the solubility of the DNAPL. More soluble DNAPLs, such as trichloroethylene, which has a solubility of 1100 mg/L, will become dissolved much more rapidly than low-solubility NAPLs, such as coal tar or creosote. However, as the DNAPL will tend to form pools on the top of low-permeability layers, the flushing liquid will only come in contact with the top of the DNAPL pool and little dissolution will actually occur (Johnson and Pankow 1992). As a result, pump-and-treat will be inefficient for mass removal in the case of DNAPLs. In spite of this inefficiency pumping still is viable as a means of plume containment.

Pump-and-treat methods have been shown to be effective in removing a large amount of more soluble contaminant mass from the aquifer during the initial phase of pumping. They are also useful in halting the spread of a plume of contamination, i.e., plume containment. However, if the contaminant concentration in the aquifer is still above the cleanup goal once a pump-and-treat project reaches the stage where the contaminant release is diffusion controlled, decades of additional pumping might be required before the aquifer is "clean." This does not mean that the pump-and-treat approach failed, it only means that it was an unrealistic expectation to attain complete remediation of an aquifer with pump-and-treat as the only remedy. The shortcomings of conventional pump-and-treat schemes have led to the development of many innovative remediation technologies, which will be discussed in greater detail later in this chapter.

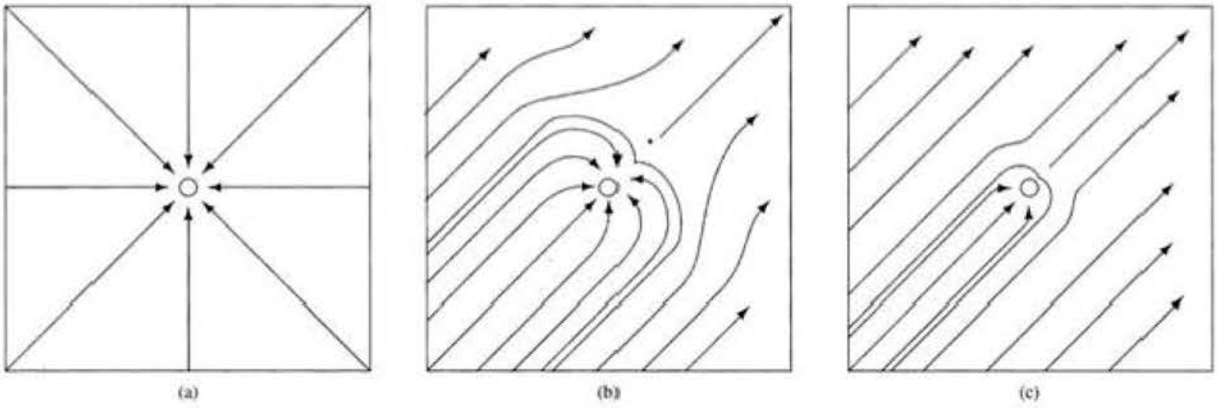
9.3.2 Capture Zones

In order to capture a plume of contaminated water, it is necessary to have one or more pumping wells located downgradient of the source area. Each well will have what is known as a **capture zone**, which is the area contributing flow to that particular well.

If the water table is flat, there is no regional flow. The capture zone of a well is radially symmetrical, centered on the well and extending as far as the edge of the cone of depression (see Figure 9.14a). If there is a slope to the water table, the groundwater flows and the capture zone are asymmetrical, with the greatest extent in the upgradient direction (Figure 9.14b). As the groundwater velocity increases, the width of the capture zone decreases for a given pumping rate (see Figure 9.14c).

The shape of the capture zone is a function of the average linear groundwater velocity, the quantity of the water being pumped from the aquifer, and the distribution of hydraulic conductivity. The upgradient extent of the capture zone depends upon the length of time over which the pumping occurs. The Wellhead Protection Area (WHPA) program was developed by the U.S. EPA that may be used to delineate capture zone. It is a semi-analytical groundwater flow simulation program that can account for multiple pumping and injection wells and delineates the area contributing flow to those wells.

FIGURE 9.14 (a) Flow lines toward a well in an aquifer with no water table gradient; (b) flow lines toward a well and the capture zone with uniform flow to the upper right of the figure; (c) flow lines toward a well and the capture zone with uniform flow to the upper right at a rate 10 times the rate of (b).



WHPA is applicable to homogeneous aquifers exhibiting two-dimensional, steady groundwater flow in an areal plane and appropriate for evaluating multiple aquifer types (i.e., confined, leaky-confined, and unconfined) (U.S. EPA 1993).

If the hydrogeology is not homogeneous or if more complex geologic or contaminant transport problems have to be accounted for, there are a number of sophisticated models available today. For instance, FLOWPATH II is a 2-D finite difference, steady-state groundwater flow model for calculation of wellhead protection zones, hydraulic heads, groundwater velocities, time related path lines, capture zones, water balances, and steady state drawdown distributions. Another model is PATH3D, which can help delineating contaminant capture zones or wellhead protection zones or can be used to evaluate the effectiveness of groundwater remedial scenarios under complex hydrogeological conditions. There are a number of other noteworthy programs and the Integrated Groundwater Modeling Center (IGWMC) at the Colorado School of Mines in Golden, CO, USA, provides reviews and links to many of those models.

9.3.3 Computation of Capture Zones

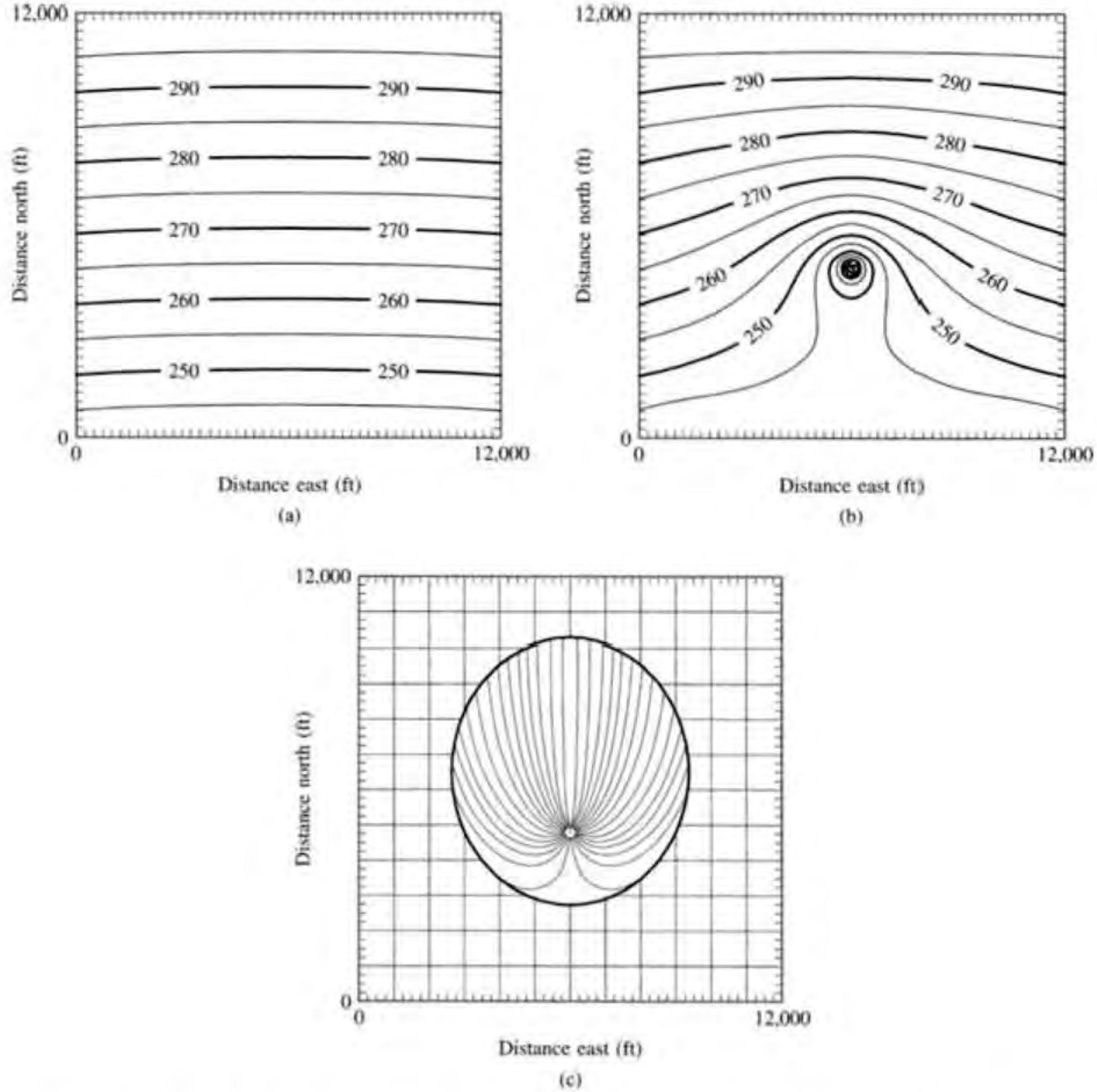
The effect of aquifer heterogeneity was illustrated by Shafer (1987). Figure 9.15a shows the initial hydraulic head for a homogeneous, isotropic, unconfined aquifer. The hydraulic-head distribution after 20 years of pumping from a single well is shown in Figure 9.15b. During this time period, the cone of depression has not spread all the way to the upgradient end of the diagram. The extent of the capture zone is shown superimposed on the model grid in Figure 9.15c. Figure 9.16a shows the distribution of hydraulic conductivity in nonhomogeneous aquifer with the same initial head distribution as the one in Figure 9.15a. In contrast to the homogenous system, the hydraulic head distribution in the nonhomogeneous aquifer with one well pumping is not symmetric and the shape of the 20-year capture zone is irregular (Figures 9.16b and c). The nonsymmetric, irregularly shaped capture zone reflects the heterogeneous distribution of the hydraulic conductivity in the nonhomogeneous aquifer. This example illustrates that ignoring aquifer heterogeneity can lead to incomplete capture of a contaminant plume.

9.3.4 Optimizing Withdrawal-Injection Systems

The rate at which groundwater restoration can be accomplished by pump-and-treat systems depends in part on how many pore volumes of water can be withdrawn from the contaminated zone. If the entire plume falls within the capture zone of one or more withdrawal wells, then we know that the plume will not spread and eventually maximum feasible restoration will occur. However, by increasing the rate (number of pore volumes of water per year) at which contaminated water is pumped, the restoration time can be decreased. For optimal conditions we also want to minimize the volume of contaminated water that is pumped, because that also must be treated.

Satkin and Bedient (1988) used a contaminant-transport model to investigate the use of various pumping and injection patterns to remediate a plume of contamination. They examined the effectiveness of seven different well patterns for various combinations of hydraulic gradient, maximum drawdown, and aquifer dispersivity. The patterns are shown on Figure 9.17.

FIGURE 9.15 (a) Hydraulic head distribution with no wells pumping. (b) Hydraulic head distribution in a homogeneous, isotropic aquifer with one well pumping. (c) Shape of the 20-year capture zone based on hydraulic head distribution of Figure 9.15b.



(a)

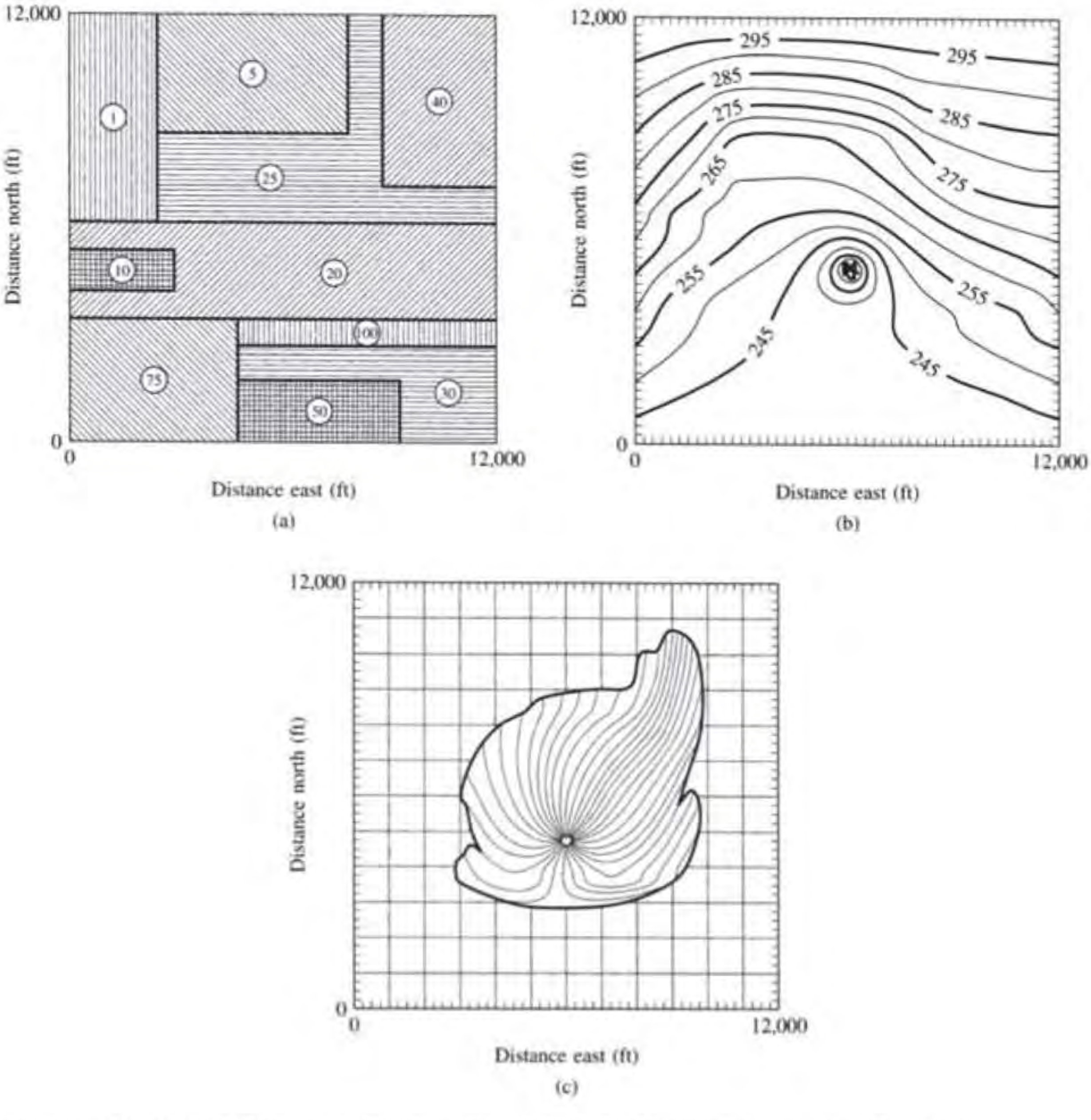
(b)

(c)

Source: J. M. Shafer. 1987. Reverse pathline calculation of time-related capture zones in nonuniform flow. *Groundwater* 25:283–289. Used with permission.

If a single pumping well is used, it must be placed so that the capture zone encompasses the plume. The closer the well can be to the center of mass of the contaminant, the faster the contamination can be removed. If the plume can be captured by a single withdrawal well, then multiple pumping wells aligned along the axis of the plume will increase the rate of cleanup over a single well by pumping a greater volume of water. The use of pumping wells without injection wells may create a problem if there isn't a receiving body of water in which to dispose of treated groundwater.

FIGURE 9.16 (a) Distribution of hydraulic conductivity in nonhomogeneous aquifer with the initial head distribution of Figure 9.15a. (b) Hydraulic head distribution in the nonhomogeneous aquifer with one well pumping. (c) Shape of the 20-year capture zone based on hydraulic head distribution of Figure 9.16b.



(a)

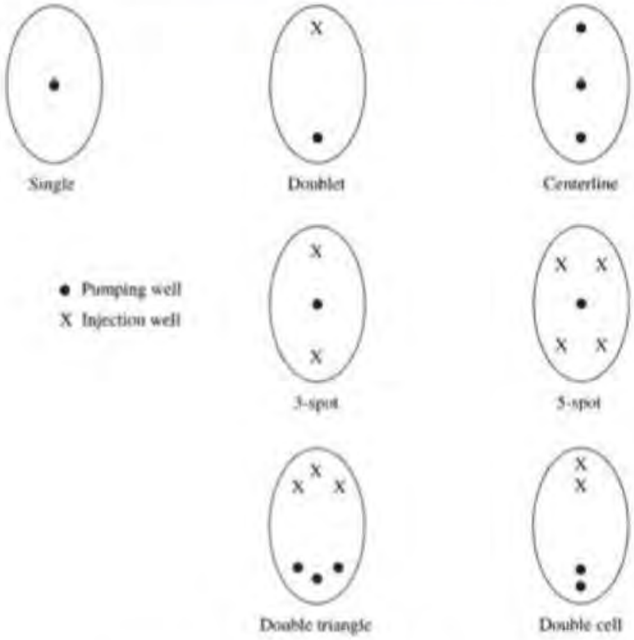
(b)

(c)

Source: J. M. Shafer. 1987. Reverse pathline calculation of time-related capture zones in nonuniform flow. *Groundwater* 25:283–289. Used with permission.

If injection wells are used in combination with withdrawal wells, cleanup time can be reduced, because steeper hydraulic gradients can be created. These steeper gradients will produce more water flowing to the withdrawal well(s) than occurs if extraction wells alone are used. We have already seen how a system of a downgradient withdrawal well in conjunction with an upgradient injection well can be used to create a circulation cell

FIGURE 9.17 Possible patterns for extraction and extraction-injection well systems.



Source: R. L. Satkin and P. B. Bedient. 1988. Effectiveness of various aquifer restoration schemes under variable hydrogeologic conditions. *Groundwater* 26:488–498. Used with permission.

to isolate the plume. This is called a doublet on Figure 9.17. Other injection-withdrawal combinations tested included the double cell and double triangle, which are variations of the doublet. Two patterns tested were based on one extraction well and multiple injection wells: the three-spot and the five-spot. When injection wells are used in conjunction with extraction wells, the treated water is disposed via reinjection. However, groundwater injection wells are prone to clogging and may need periodic maintenance (Fetter 1994). Additionally, states, provinces, or regions may have water-quality standards for any water that is reinjected; many locales require a permit for injection wells.

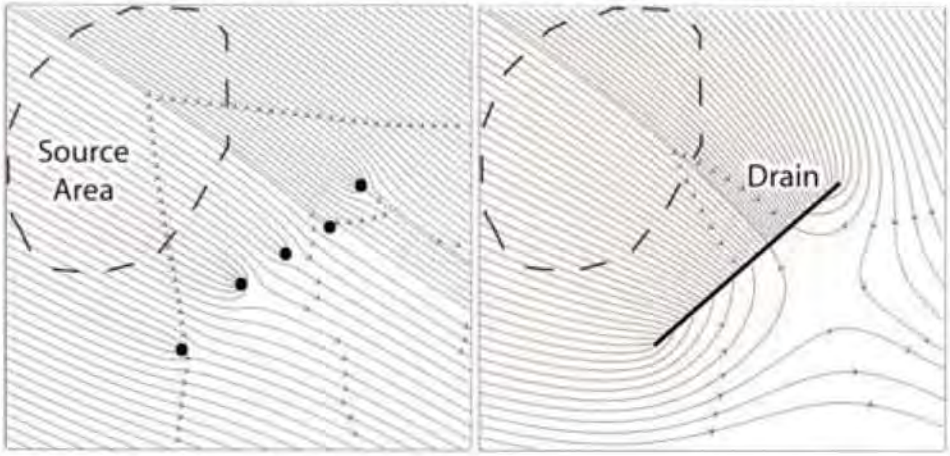
Satkin and Bedient (1988) found that the best well pattern for cleanup was highly site-specific. They also found that even with the same well pattern, variation in the placement of the wells yielded different cleanup times. When the hydraulic gradient is low, the doublet, double cell, and three-spot patterns were very effective. Under conditions of high hydraulic gradient, the centerline was most effective. In this pattern the downgradient injection well, which must be located beyond the leading edge of the plume, creates a hydraulic barrier to further migration of the plume. The five-spot pattern was not found to be very effective under any conditions.

9.3.5 Permanent Plume Stabilization

Decades of experience with pump-and-treat technology showed that in most cases it is not feasible or even technically possible to fully remediate a badly contaminated aquifer by pump-and-treat technology. This is especially true if the source cannot be located and removed, for example, if there are nonbiodegradable residual DNAPLs present in a fractured rock aquifer. For such aquifers the only feasible technology might well is insufficient to prevent the plume from growing. Pumping at the source zone and downgradient improved the situation but some contaminated groundwater still escaped downgradient. Only the installation of a mid-gradient well prevented the escape of contaminated groundwater. The modeling results underline the importance of source control pumping and the establishment of sufficiently large downgradient capture zones to prevent continued offsite migration of contaminated groundwater.

A different approach to plume containment is to construct a **French drain** perpendicular to the direction of the plume migration. Such a drain system is typically constructed by excavating a ditch to the maximum depth of the plume and back filling it with gravel or other highly permeable material. Embedded at the base of the trench is a horizontal perforated pipe that connects to a vertical well. Contaminated water intercepted by the trench is collected by the pipe and then pumped to the surface for further treatment. As shown in Figure 9.19, a French drain may provide more effective plume containment than a series of extraction wells (Cohen et al. 1997). These drain systems are limited to comparably shallow plumes in unconsolidated material because digging deep trenches (>>30 m or >100 ft) is typically cost prohibitive and often not feasible, particularly if the sediment is unstable and prone to caving. Constructing French drains in bedrock is generally possible, but typically too expensive.

Figure 9.19 Compared to a line of conventional pump-and-treat wells (left), a plume emanating from an up gradient source zone can be effectively intercepted by a trench drain constructed perpendicular to the main axis of groundwater flow (right).



Source: Cohen et al. 1997.

9.4 Treatment of Extracted Groundwater

9.4.1 Overview

It is often necessary to withdraw water during site remediation projects and that water must be treated *ex situ* according to the type of contamination. Different types of treatment are needed for water contaminated with heavy metals or that is contaminated by dissolved organic compounds. Similarly, the treatment approach will be different for compounds that are volatile versus those that are not, or those pollutants that can be chemically or physically destroyed or converted into non-toxic compounds versus those that cannot. Most of the treatment techniques that are used were developed for wastewater and have been adapted to contaminated groundwater. Generally, there are two types of treatment approaches (1) separation and (2) destruction technologies. Examples for the former include adsorption to granular activated carbon (GAC), or air stripping. Destruction technologies include, for instance, UV oxidation and other advanced oxidation processes or biological treatment methods. These and other *ex situ* treatment technologies for contaminated groundwater are described in detail on the Federal Remediation Technologies Roundtable (FRTR) or EUGRIS websites and other online information depositories introduced in Section 9.1. Some of these treatment technologies require the contaminated matrix, soil or groundwater, to be transported to the treatment facility; others can be easily set up on the contaminated site. The treatment methods for contaminated soil and sediment are not covered in this chapter.

The design of a treatment system must be cost effective. To this end the designer must consider the trade-off between capital costs and operating costs. Extraction systems can be designed by the hydrogeologist to withdraw the maximum volume of water in the shortest period of time. This yields the fastest, but not necessarily the most cost-effective cleanup of the aquifer. The size of the treatment plant is dictated by the maximum rate by which water will be pumped for treatment. The capital costs for the treatment plant include the treatment vessels, pumps, piping, and tanks. The greater the flow rate at which contaminated water is pumped through the treatment system, the larger these items must be and the greater the initial capital costs.

Operating costs include the electricity to run the plant, the cost of chemicals, the labor to operate the plant, and the cost of repairs. Some of the operating costs will be continuous no matter how long the project lasts (e.g., the cost of chemicals used to treat the water). If the same total volume of water is treated, the same amount of chemicals will be needed, no matter how long or short the treatment period. Other costs, such as labor, depend primarily upon the length of time of the operation. If the total volume of contaminated water is treated over a very short period of time, there will be high initial capital costs for the large-capacity plant and low operating costs because of the short time period. If the same volume of water is pumped over a longer period of time, the capital costs will be lower, since a smaller treatment plant is needed, but the operating costs will be higher. The smallest treatment plant possible is that needed to treat the quantity of water generated by the minimum pumping rate, which is just high enough to capture the plume. There will be some optimum treatment rate that minimizes the combined capital and operating costs.

9.4.2 Treatment of Inorganic Contaminants

The majority of inorganic contamination needing treatment consists of metals, which can be removed by precipitation or adsorption. Often the treatment involves mixing of reactive agent(s) into the extracted contaminated water. Many metal hydroxides precipitate at a specific alkaline pH value. For these metals, adjustment of pH by adding lime can cause precipitation of the metal hydroxide, which is removed via a clarifier followed by filtration. Ferrous iron can be removed by aeration to create ferric iron, which will precipitate at a slightly alkaline pH. Hexavalent chromium must first be reduced to the trivalent state by lowering the pH to 3 and then adding a reducing agent such as sulfur dioxide. The trivalent chromium can then be precipitated as a hydroxide by raising the pH above the neutral value. Arsenic can be coprecipitated with iron by adding dissolved iron at a pH of 5 to 6 and then raising the pH with lime to between 8 and 9. Arsenic also adsorbs to activated alumina.

Inorganic compounds can be removed by ion exchange. This process uses a resin to adsorb and retain anionic or cationic contaminants from groundwater. In place of the toxic ions, the resin releases benign anions or cations, such as chloride and calcium. When the resin becomes saturated after all of the resin's functional groups have been occupied, it needs to be recharged before reuse, or possibly disposed and replaced. This treatment approach is used commonly for nitrate, which cannot be removed by precipitation. Ion exchange has also been used for removing radiogenic isotopes, like uranium (Botha, Bester, and Hardwick 2009). Inorganic contaminants can also be removed by reverse osmosis and electro dialysis. In reverse osmosis, water is pressured to flow through a semi-porous membrane. While the water molecule passes through the membrane, many molecules and ions cannot and are retained on the membrane surface. In case of electro dialysis, flow through a membrane is induced by an electric potential and because the membranes are cation- or anion-selective, either positive ions or negative ions will flow through and can be exchanges for benign ions. This method has been used to remove radium, uranium, arsenic, nitrate, perchlorate, and hardness from drinking water (U.S. EPA 2015) or to remove cooper, chromium and arsenic from chromated copper arsenate (CCA) treated timber waste water (Ribeiro, Mateus, and Ottosen 2000).

9.4.3 Treatment of Dissolved Organic Contaminants

Many of the organic contaminants found in groundwater are volatile. They can be stripped from the water by exposing the water to a flow of air. This is accomplished in an air-stripping tower (Figure 9.20). The tower is a tall cylinder filled with an inert packing material, typically made of polypropylene. The packing material is designed to have a very high porosity and a large total surface area. The contaminated water is sprayed into the top of the tower onto the packing material. A blower attached to the bottom of the tower forces air up the tower at the same time that the water, which was broken up into droplets by the spray nozzles, trickles down the packing material. The volatile organic chemicals vaporize from the water into the air and are expelled out of the top of the tower. Care must be taken that emissions from the air-stripping tower do not create an air-pollution problem. For this reason, the exhaust from the air stripper is typically treated by sorption onto activated carbon or a thermal treatment unit, as can be the case for gasoline type vapors. For typical air stripping towers 4.6 to 6 m (15 to 20 ft) in height and containing conventional packing, removal efficiencies of VOC are around 99%. The removal efficiencies can be improved by adding a second air stripper in series with the first, heating the contaminated water, or changing the configuration of packing material (FTRC 2015). A potential problem with air stripping is biological fouling, which describes the buildup of biofilms growing on the inside of the air stripping tower. If not attended to, biofouling can lead to decreasing treatment and eventually clogging of the system. Another common problem with air strippers is precipitation of iron or other minerals. Typically, if the treated groundwater contains more than 5 mg/liter iron or its hardness is greater than 800 mg/liter (FRTR 2015), it becomes likely that mineral precipitates will build up inside the stripper tower. Mechanical filters, such as sand beds, might be needed to filter the precipitated iron from the wastewater stream

An uncontaminated, confined sand aquifer that was 1.5 m (5 ft) thick was instrumented with a line of injection and extraction wells located 6 m apart. The direction of groundwater flow from the injection to the extraction wells was parallel to the regional hydraulic gradient. Intermediate sampling wells were placed at distances of 1, 2.2, and 4 m (3 to 12 ft) from the injection wells. Depending upon the injection and withdrawal rates, travel times from the injection wells to the withdrawal wells were from 20 to 42 hr. When oxygenated water was injected into the aquifer prior to the biostimulation experiments, the oxygen was transported to the extraction wells with little loss.

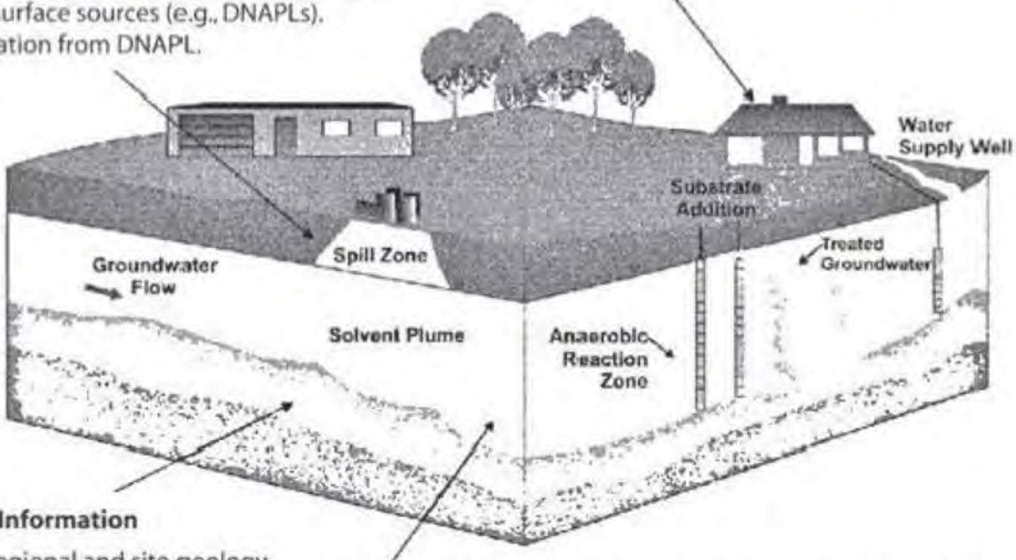
The compounds that were selected for study were vinyl chloride (VC), *trans*-1,2-dichloroethene (t-DCE), cis-1,2-Dichloroethene (c-DCE), and trichloroethene (TCE). When these were injected prior to biostimulation, they were retarded in the rank order of TCE > t-DCE > c-DCE > VC. It was found that with a long period of injection prior to biostimulation, the sorption capacity of the aquifer could be saturated with respect to TCE, t-DCE, and c-DCE. After 1000 hr. of injection, the concentration of these compounds in the monitoring well located 1 m (~3 ft) from the injection well was found to be 90 to 95% of the injected concentration.

After the aquifer reached steady-state concentrations of the organic halides, it was biostimulated by injecting alternating pulses of dissolved oxygen and methane, along with continuous injection of the organic halides. The methane acted as the primary substrate (electron donor) for the growth of indigenous methane-utilizing bacteria, while the oxygen was the electron acceptor. The organic halides were degraded by cometabolism, a process by which the methantrophic bacteria that are utilizing the methane produce enzymes that are able to degrade the chlorinated ethenes. During the biostimulation experiments, decreases in concentration of both methane and the organic halides were observed. Within 2 m (6 ft) of travel through the aquifer, VC was reduced by 90 to 95%, t-DCE by 80 to 90%, c-DCE by 45 to 55%, and TCE by 20 to 30%. Residence times in the aquifer were only 1 to 2 days for this amount of biodegradation. It took about three weeks for the biostimulation experiment to reach these steady-state rates of reduction. An intermediate degradation product, *trans*-dichloroethene epoxide, was detected. When the injection of methane was halted, the concentration of the epoxide quickly decreased and the concentration of the halogenated ethenes slowly increased. However, when the rate of methane addition was increased beyond a certain concentration, it was shown to reduce the rate of transformation of VC and tDCE. Thus, while methane was necessary for stimulating *in situ* aerobic biotransformation, there appears to be an optimal concentration beyond which it inhibits the process.

9.11 Conceptual Site Models

The bioremediation approach serves as an example for the complexity of the biochemical and hydrogeologic interactions and their dependency on aquifer characteristics and the physical/chemical properties of the contaminant(s). Failure to understanding these conditions can determine the success or failure of site cleanup activities. Therefore, the development of a conceptual model of the site is an essential part of the site remediation process. Such a model is referred to as a conceptual site model (CSM). A CSM develops during the course of a site investigation. Elements of a CSM include at minimum a conceptualization of the processes that determine contaminant releases, contaminant migration, and the relationship between contaminant sources and receptors. The CSM is used to integrate all site information and data and to determine whether data gaps exist and whether additional information needs to be collected at the site. The model is used furthermore to facilitate the selection of remedial alternatives and to evaluate the effectiveness of remedial actions in reducing the exposure of environmental receptors to contaminants (ASTM 2014). The CSM should be maintained and refined as new information and data is collected from the initial assessment through site closeout. Different types of CSM are common, including text documents and pictorial and graphical depictions of current and future site conditions. Parsons Corporation (2004) provides an example of the elements of a graphical CSM (Figure 9.38). Typical CSM information needs and other elements of a CSM for sites contaminated with unexploded ordnance and/or other hazardous, toxic, and radioactive waste is provided by the U.S. Army Corp of Engineers (2012).

FIGURE 9.38 Elements of a Conceptual Site Model.



Risk Assessment

- Current and potential receptors.
- Completed pathways?

Contaminant Source Information

- Location and nature of previous contaminant sources.
- Locations of subsurface sources (e.g., DNAPLs).
- Flux of contamination from DNAPL.

Hydrogeological Information

- Description of regional and site geology.
- Stratigraphy that may provide preferential pathways for, or barriers to, contaminant transport.
- Depth to ground water.
- Hydraulic gradients (horizontal and vertical).
- Hydraulic conductivity (degree of heterogeneity).
- Groundwater / surface water interactions.

Contaminant Distribution, Transport, and Fate Parameters

- Phase distribution of contaminant (gaseous, aqueous, sorbed, free-phase DNAPL or residual DNAPL) in the unsaturated and saturated zones.
- Spatial distribution of subsurface contaminants.
- Temporal trends in contaminant concentrations.
- Contaminant natural attenuation processes (destructive and nondestructive).
- Geochemical indicators (aerobic / anaerobic).

Source: Parsons Corporation 2004.

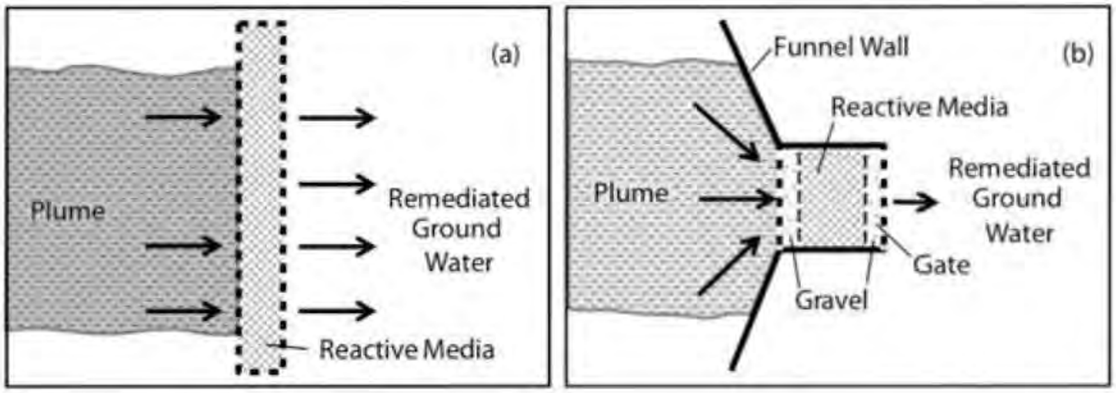
9.12 Permeable Reactive Barriers

A permeable reactive barrier (PRB) is a subsurface emplacement of reactive materials through which a dissolved contaminant plume must move as it flows, typically under natural gradient conditions. Treated water exits on the other side of the PRB. This *in* *situ* method for remediating dissolved-phase contaminants in groundwater combines a passive chemical or biological treatment zone with subsurface fluid flow management (U.S. EPA 2015d). The purpose of a PRB is to intercept a contaminant plume and prevent it from migrating to downgradient receptors, such as drinking water wells.

The concept of placing reactive materials in the path of a plume was developed based on observations by Reynolds et al. (1990). The authors noticed that at their field site concentration of dissolved chlorinated compounds were systematically lower in wells with galvanized iron casing compared to wells constructed from non-metallic pipe material. Laboratory experiments showed that metallic or zero valent iron (ZVI) reacted with the chlorinated compounds and degraded them to non-toxic products, such as ethane and ethane (Gillham and O'Hannesin 1994). The first field trial of a PRB was carried out by Gillham and O'Hannesin on the Canadian Air Force Base Borden, Ontario in 1991. A trench of up to 6 m (20 ft) in length and 2.5 m (8 ft) deep was excavated and backfilled with a mix of 22% of granular iron from a local foundry and 78% coarse sand. The total volume of the reactive matrix was 20 m^3. The groundwater flow velocity in the unconfined sandy aquifer at the site was 9 cm/day (0.3 ft/day). The groundwater concentration of TCE was 258 mg/L and 68 mg/L for PCE. After installation, approximately 90% of the TCE and 86% of the PCE were removed within this proto-type PRB system, with no measurable decrease in performance over the first five year duration of the test. All degradation intermediates, including *cis*-1,2-DCE, were degraded within the reactive barrier. Changes in water chemistry indicated that calcium carbonate was precipitating within the reactive material. However, the clogging caused by the precipitates was inconsequential for the performance of the system within the five year study period. The authors concluded that full removal would have been achieved by increasing the amount of ZVE (O'Hannesin and Gillham 1998). Since these early trials, more than 200 reactive barriers have been installed and PRB technology is now an accepted practice for groundwater remediation, particularly for the treatment of dissolved chlorinated VOC plumes (ITRC 2011).

In situ PRB systems are typically constructed by digging a continuous trench perpendicular to the flow direction of a groundwater plume (Figure 9.39). After excavation, the trench is backfilled with a mix of reactive material and coarse sand and gravel, which provides the mix with a hydraulic permeability and porosity that is greater than the surrounding natural sediments. The length and depth of the PRB is determined by the dimensions of the groundwater plume, i.e., the trench must be large enough to capture the entire plume in both horizontal and vertical direction. If possible, the trench is anchored in a less permeable stratum, such as a clay layer, to prevent the plume from diving under the treatment system. In some cases, funnel-and-gate PRB systems have been installed in which an impermeable barrier blocks the advancing plume and redirects (funnels) the flow of contaminated groundwater through an opening (gate) in the wall and into a PRB system (ITRC 2005a). A funnel-and-gate system is depicted in Figure 9.39. The length of PRB systems is limited by site conditions and typically ranges from a few meters to a few hundred meters. The depth, however, is limited by the equipment available to excavate the trench. Trenches excavated with conventional equipment, such a back hoes or chain trencher, are comparably shallow (10 to 15 m or 33 to ~50 ft). Depths of 20 m (66 ft) or more can be achieved by caisson installation or cofferdam/sheet pile methods. Alternatively, the reactive material can be mixed *in situ* into the treatment zone or slurries of reactive materials can be directly injected into the subsurface. The cost of constructing the trench and backfilling it with reactive material is the major cost driver of this remediation technology.

FIGURE 9.39 Permeable reactive barrier (PRB) designs (map view). (a) Continuous trench and (b) Funnel-and-gate systems.



The thickness of the PRB wall is a critical design parameter. It depends on hydrogeologic factors, (such as groundwater flow velocities and flow directions which may change over the seasons), the strength and chemical make-up of the source zone including which contaminants are present and how much mass of dissolved contaminant must be treated, and the reactivity of the PRB material, including the geochemical conditions that can influence the reactive material, such as the pH of the groundwater. The reactivity of the material inside a PRB can be quantified in terms of a reaction rate constant or the half-life time of the contaminant coming in contact with the reactive material. Because some contaminants, including PCE and TCE, undergo sequential degradation, which involves the production of toxic intermediates, such as vinyl chloride, reaction rates for each compounds need to be taken into consideration. If the flow-through thickness and contaminant residence time inside the PRB is underestimated, still-contaminated water will emerge on the downgradient side of the wall. It is therefore not surprising that extensive laboratory and field tests are required to ensure the field performance of a PRB system. A lot of practical information about the proper installation of PRB systems has been accumulated over the past two decades and many PRB installations manuals and guidance documents are available on the internet, including Gavaskar et al. (2000) and ITRC (2011).

Zero-valent iron based PRBs are most commonly used for the *in situ* treatment of chlorinated aliphatic VOC, such as PCE and TCE. The reactions involved in the degradation of chlorinated VOC by metallic iron (Fe^0) within a PRB are abiotic in nature. Zero valent iron is a mild reductant and can react with dissolved oxygen (Eqn. 9.1) and to some extent with water (Eqn. 9.2):

$$2Fe^0_{(S)} + 4H^+_{(aq)} + O_{2(aq)} \rightarrow 2Fe^{2+}_{(aq)} + 2H_2O \qquad \textbf{(9.1)}$$

$$Fe^0_{(S)} + 2H_2O \rightarrow Fe^{2+}_{(aq)} + H_{2(aq)} + 2OH^-_{(aq)} \qquad \textbf{(9.2)}$$

These two equations illustrate the corrosion (=oxidation) of iron when coming in contact with oxygen or water. The two electrons released during the oxidation of iron can be readily accepted by chlorinated hydrocarbons, which are degraded via reductive dehalogenation, as shown in Equation 9.3

$$\begin{array}{ll} Fe^0 \rightarrow Fe^{2+} + 2e^- & \text{Oxidation} \\ RCl + 2e^- + H^+ \rightarrow RH + Cl^- & \text{Reduction} \\ \hline Fe^0 + RCl + H^+ \rightarrow Fe^{2+} + RH + Cl^- & \text{Net Reaction} \end{array} \qquad \textbf{(9.3)}$$

The products of the reductive dechlorination reaction are chloride (Cl^-), ferrous iron (Fe^{2+}), less chlorinated hydrocarbons, and hydrogen. Dechlorination of chloroethenes and chloroethanes is complete with ethene and ethane as the final carbon-containing compounds, respectively (Orth and Gillham 1996; Fennelly and Roberts 1998). The corrosion of the iron can generate large amounts of iron oxides and (oxy)hydroxide precipitates, which may eventually decrease the porosity and permeability of the reactive material within the PRB; particularly at the upgradient side of the barrier. However, these iron precipitates can convert to magnetite, which does not passivate the reactive surface of the iron. Also, field experiences from many PRB sites indicate that the loss of permeability due to precipitation is a relatively slow process that takes decades to cause significant changes in the hydraulic performance of the system. If installed properly, it is therefore likely that the dechlorination reaction is sustainable for many years of PRB operation (EPA 1998).

The degradation of chlorinated hydrocarbons by ZVI is a stepwise process during which intermediates are produced, such as *cis*-1,2-dichloroethene, vinyl chloride or chloroacetylene in cases where the parent compound is TCE or PCE. The degradation reactions are typically described using pseudo first-order kinetics with respect to the halogenated hydrocarbon, with the rate constant relatively insensitive to the initial hydrocarbon concentration (IRTC 2011).

$$C = C_0^{-k't}$$

or:

$$\ln\left(\frac{C}{C_0}\right) = -k't$$

where C_0 and C are the concentrations of the chlorinated compound of the influent and at time t, respectively. The pseudo-first order rate constant is k, which equals the first order rate constant, k, when the concentration of the iron remains constant. Dehalogenation rates vary for the different halogenated contaminants. The primary determinant of degradation rate is the iron surface area, i.e., the surface area of iron per unit volume of pore water. For this reason, some PRB designs are based on nanoscale iron particles, which have larger surface areas and higher surface reactivity compared to conventional granular iron. Nanoscale iron particles range in size from approximately 10 to 100 nm and have a high iron content (>99.5% Fe) (Zhang 2003).

The reaction rates can be enhanced further by coating the iron particles with metallic catalyst, such as palladium (Li and Farrel 2000). One advantage of nanoscale iron particles is that slurries of these particles can be injected directly into the treatment zone. This approach alleviates the need of excavating a trench and back-filling it with mixes of ZVI and highly permeable sand/gravel materials.

Dissolved chlorinated compounds were the first groundwater contaminants treated by *in situ* PRB systems using metallic iron as the reactive material. Since then, the list of ZVI treatable compounds has rapidly expanded and now includes many other organic and inorganic contaminants (Table 9.2). For instance, metallic iron can **transform** explosives, such as TNT (Johnson and Tratnyek 2008), and pesticides, e.g., Lindane (U.S. EPA 2002) or can **immobilize** inorganic ions, such as arsenic (VI) and chromium (VI). Particularly metals that occur as anions exhibit a high degree of mobility because anions do not readily sorbed to the predominantly negatively-charged aquifer materials. For example, chromium (VI) is usually speciated as chromate, CrO_4^{2-}, which is a known carcinogen. The anion is comparably soluble under typical near-neutral pH and only slightly negative Eh conditions in typical aquifers. However, when reduced to trivalent Cr(III), relatively non-toxic and little soluble precipitates are formed. The immobilization of Cr(VI) by iron is a two-step process: first, Cr(VI) is reduced to Cr(III) (Eqn. 9.4). Subsequently, the Cr(III) precipitates as Fe(III) oxyhydroxide (Eqn. 9.5) (U.S. EPA 1998):

$$CrO_4^{2-} + Fe^0 + 8H^+ \rightarrow Fe^{3+} + Cr^{3+} + 4H_2O \tag{9.4}$$

$$(1-x)Fe^{3+} + (x)Cr^{3+} + 2H_2O \rightarrow Fe_{(1-x)}Cr_xOOH_{(s)} + 3H^+ \tag{9.5}$$

The mechanisms of Cr(VI) reduction by Fe(0) and their effects on the pH and Eh conditions of the system have been described by Powell et al. (1995) and Powell and Puls (1997). At some sites, Cr(VI) occurs together with other contaminants, such as TCE. Research has shown that it is possible to simultaneously treat both chromium and TCE with ZVI (U.S. EPA 1998).

While ZVI remains the most widely used reactive material used in PRB systems, an increasing number of new reactive materials and variations of the PRB based treatment approach are being developed and tested. These advances are greatly expanding the number of treatable groundwater contaminants. They also make it possible to apply this technology to hydrogeologic environments other than the unconsolidated aquifers for which PRB was initially developed. For example, a fractured bedrock aquifer comprised of shale and siltstone is contaminated with PCE at a manufacturing plant in northern New Jersey, USA (U.S. EPA 2011b). The main source area is located in shallow bedrock to a depth of approximately 13 m (42.5 ft) below ground surface, with some contamination in deeper parts of the aquifer. The lateral extent of the PCE plume is approximately 25 m (80 ft) by 37 m (120 ft). The plume was approximately 1.2 km (4,000 ft) in length prior to treatment. A pump-and-treat system and later, an enhanced bioremediation system were installed for containment of the PCE plume. After observing some reduction of contaminant flux, a nanoscale zero-valent iron injection was proposed as a more aggressive strategy. Before the injection of the nanoscale particles into the bedrock, the hydraulic communication within the fracture network was improved by hydrofracturing. This technology involves applying

TABLE 9.2 Common environmental contaminants that can be transformed by ZVI, including bimetallic and nanoscale iron particles.

Chlorinated methanes	**Chlorinated ethenes/ethanes**	**Chlorinated benzenes**	**Trihalomethanes**
Carbon tetrachloride (CCl_4)	Tetrachloroethene (C_2Cl_4)	Hexachlorobenzene (C_6Cl_6)	Bromoform ($CHBr_3$)
Chloroform ($CHCl_3$)	Trichloroethene (C_2HCl_3)	Pentachlorobenzene (C_6HCl_5)	Dibromochloromethane ($CHBr_2Cl$)
Dichloromethane (CH_2Cl_2)	*cis*-Dichloroethene ($C_2H_2Cl_2$)	Tetrachlorobenzenes ($C_6H_2Cl_4$)	Dichlorobromomethane ($CHBrCl_2$)
Chloromethane (CH_3Cl)	*trans*-Dichloroethene ($C_2H_2Cl_2$)	Trichlorobenzenes ($C_6H_3Cl_3$)	
	1,1-Dichloroethene ($C_2H_2Cl_2$)	Dichlorobenzenes ($C_6H_4Cl_2$)	
	Vinyl chloride (C_2H_3Cl)	Chlorobenzene (C_6H_5Cl)	
	1,1,1-trichloroethane ($C_2H_3Cl_3$)		
	1,1,2-trichloroethane ($C_2H_3Cl_3$)		
	1,1-dichloroethane ($C_2H_4Cl_2$)		
Other polychlorinated hydrocarbons	Pesticides	Organic dyes	Other organic contaminants
Dioxins	DDT ($C_{14}H_9Cl_5$)	Orange II ($C_{16}H_{11}N_2NaO_4S$)	TNT ($C_7H_5N_3O_6$)
Pentachlorophenol (C_6HCl_5O)	Lindane ($C_6H_6Cl_6$)	Chrysoidine ($C_{12}H_{13}ClN_4$)	RDX ($C_3H_6N_6O_6$)
PCBs		Tropaeolin O ($C_{12}H_9N_2NaO_5S$)	N-nitrosodimethylamine (NDMA) ($C_4H_{10}N_{20}$)
		Acid Orange	
		Acid Red Arsenic (AsO_3^{-4})	
Heavy metal ions	Radiogenic ions	Inorganic ions	
Mercury (Hg^{2+})	Uranium (U VI)	Perchlorate (ClO^{-4})	
Nickel (Ni^{2+})	Technetium (Tc VII)	Nitrate (NO^{-3})	
Silver (Ag^{+})		Dichromate ($Cr_2O_2^{-7}$)	
Cadmium (Cd^{2+})		Selenium (Se IV)	
		Arsenic (As VI)	

Source: Modified after Zhang 2003 and U.S. EPA 1998.

high hydrostatic pressures to the well wall until the solid bedrock fractures. The newly opened fractures permit enhanced injection and farther reach of the nanoparticle slurry into the bedrock. Following hydrofracturing, approximately 800 pounds of nanoscale iron particles was delivered through four injection wells. Performance monitoring of the ZVI injection indicated significant impacts on source area geochemistry, including increased pH levels (~9) and low ORP values (-500 mV). Although it is likely that the iron particles did not reach all contaminated areas of the bedrock aquifer, it appears that amount of injected iron was sufficient to control both the primary PCE source and any back diffusion from the shale and siltstone matrix.

Innovative reactive materials for PRB include surfactant-modified zeolites, metal hydroxides or carbonates, organoclays, peat moss, mulch, compost and agricultural waste products (Thiruvenkatachari et at. 2008). Zeolites are clay minerals that have an elevated permeability (for a clay) and a high capacity for cation exchange. When coated with non-ionic surfactants, the surface of the zeolites becomes more hydrophobic, which makes it attractive to non-polar organic compounds. When modified with cationic surfactants, the zeolite surface has a positive charge and hence a greater affinity for anions, such as dissolved chromate (Bowman 2003; Misaelides 2011). Surfactant modified zeolites retain some of their cation ion exchange capacity. Peat moss has an affinity for both heavy metal ions, such as nickel or uranium and anions, e.g., chromate. Compounds like mulch or agricultural waste products used in PRBs are intended to be long-term sources of organic carbon or, in case of compost, serve as a source of nutrients (IRTC 2011). For instance, Lu et al. (2008) investigated the performance of pilot-scale permeable reactive barrier filled with plant mulch that was installed at Altus Air Force Base in Oklahoma, USA in 2002. The barrier was 139 m long (~450 ft), 7 m deep (~2 m), and 0.5 m (1.6 ft) wide and was constructed to treat trichloroethylene (TCE) contamination in groundwater emanating from a landfill. Data from over four years' monitoring indicated that the PRB stimulated TCE degradation to cis-DCE and vinyl chloride. Ongoing biodegradation reactions were corroborated by the detection of TCE degrading bacteria DNA (*Dehalococcoides*) and the detection of vinyl chloride within and downgradient of the PRB.

Systems like the one described by Lu et al. (2008) are also called **biowalls** or **bio barriers**. These *in situ* biowalls use solid low-cost organic materials, such as mulch or compost, to stimulate anaerobic degradation of chlorinated solvents, energetic (e.g., perchlorate) and explosive compounds (e.g., TNT, anions (nitrate and sulfate), and heavy metals (e.g., chromium and cadmium). Biowall materials can be amendment with, for example, emulsified vegetable oil, to stimulate both biotic and abiotic degradation processes. This permits to optimize biowall performance based on the type of contaminant(s) present and the desired degradation pathway(s) to be stimulated (Air Force Center for Engineering and the Environment 2008). Typically, biowalls stimulate anaerobic degradation processes, including reductive dechlorination and biotic anaerobic oxidation, and therefore are most often used for treating dissolved chlorinated compounds like PCE and TCE and their degradation products (DCE isomers and vinyl chloride). According to the ITRC (2011), an advantage of biological PRB systems over purely abiotic systems, such a ZVI, is that the treatment processes may extend downgradient of the constructed treatment zone due to migration of soluble organic carbon, enabling the effects of anaerobic degradation beyond the biowall. In addition, the biowall system can be amended with specific bacteria (bioaugmentation) to target one or multiple contaminants and accelerate their degradation. A drawback is that the longevity of biowalls is anticipated to be shorter than that of ZVI walls and replenishment of organic substrate may be required.

The geochemistry of the solution inside a PRB system and downgradient can be adjusted by materials to buffer pH (e.g., limestone gravel) or to adjust the redox potential and further stimulate abiotic biogeochemical transformation processes (e.g., addition of reactive iron sulfite minerals, such as pyrite or mackinawite). The redox conditions in the treatment zone can also be manipulated by injecting sodium dithionite solution. The dithionate reduces ferric iron (Fe III) that is naturally present in the aquifer material to ferrous iron (Fe II). The presence of Fe(II) in the treatment zone can reduce, for example, soluble Cr(VI) to Cr(III) precipitates (Naftz et al. 2002). Also, the injection of oxidants, like hydrogen peroxide (H_2O_2) or potassium permanganate ($KMnO_4$) into the PRB can create strongly oxidizing conditions that are suitable for the *in situ* chemical oxidation and destruction of many organic contaminants, including BETX and other petroleum hydrocarbons (Thiruvenkatachari et at. 2008). Finally, sorbing barriers systems have been developed which use granular activated carbon or ion exchange materials. However, these systems have a limited live time and need to be replacement when the capacity of the sorbent is exhausted.

There now are a great variety of the reactive materials and amendments that permit tailoring the PRB treatment to specific contaminants, including once that cannot be treated with the original ZVI approach, e.g., BTEX compounds. Barriers of different chemistries may also be placed sequentially which further increases the treatment options for contaminated site managers. It is likely that future research into PRB system will further enhance the applicability of this remediation approach.

■ 9.13 Chemically-Enhanced *In Situ* Flushing

Some chemicals, such as surface active agents (surfactants), complexing agents (cyclodextrins) or cosolvents (alcohols), can increase the solubility of otherwise slightly soluble hydrophobic organic contaminants, such as petroleum hydrocarbons or chlorinated solvents. In case of some metals or ionic organic contaminants, a similar solubility enhancing effect can be achieved by injecting acidic, basic, or reducing solutions. When injected into the aquifer and flushed through the contaminated source zone, these solubility enhancing agents increase the aqueous phase concentration of the contaminants, sometimes by orders of magnitude. After its passage through the treatment zone, the flushing solution is extracted and treated at the surface. Therefore, in its most basic form, chemically-enhanced flushing technology can be considered an enhancement of pump-and-treat in which water is the flushing solution. Compared to P&T, chemically-enhanced flushing is a much more aggressive and relatively rapid treatment approach with treatment durations often an order or two magnitudes shorter than P&T (ITRC 2009a).

In situ flushing is considered a mature remediation technology. The chemically-enhanced flushing approach is used predominantly to remediate source zones, particularly residual NAPL compounds. It is less well suited for the treatment of dissolved plumes or contaminants residing in the unsaturated zone. Flushing is most efficient in relatively homogeneous and permeable (hydraulic conductivity $>10^{-3}$ cm/sec) soil the biowall system can be amended with specific bacteria (bioaugmentation) to target one or multiple contaminants and accelerate their degradation. A drawback is that the longevity of biowalls is anticipated to be shorter than that of ZVI walls and replenishment of organic substrate may be required.

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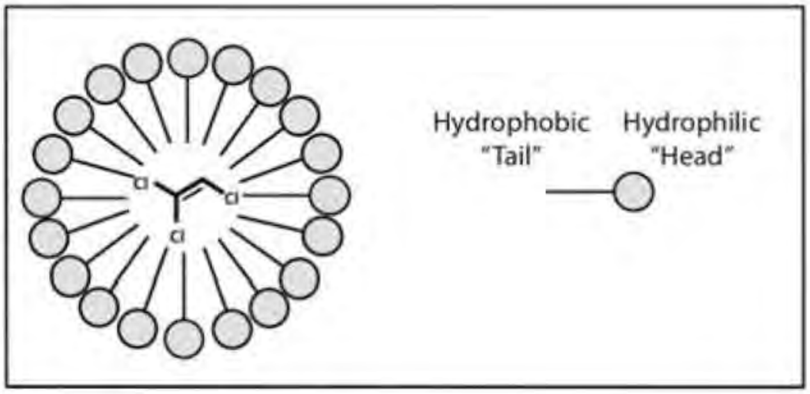
(Naval Facilities Engineering Command 2002). Heterogeneous aquifer conditions, including fractured bedrock aquifers, typically stand in the way of effectively flooding the treatment zone because lower permeable zones may be by-passed. Chemically-enhanced flushing is sometimes used in combination with other *in situ* remediation technologies, such as bioremediation or *in situ* oxidation (e.g., Dugan et al. 2010). Although their effect on the solubility of contaminants is similar, there are major differences between surfactant, cosolvent, or complexing agents. The following sections provide a brief overview of these agents. One disadvantage is that field applications typically have limited areal extent. For further readings, there have been a great number of papers, books, and manuals written about these flushing agents (e.g., Keuper et al. 1997; Lowe et al. 1999; Ward et al. 2000; Boving and Brusseau 2000; Naval Facilities Engineering Command 2002; 2003; ITRC 2003; Pennel et al. 2014).

9.13.1 Surfactant Enhanced *In Situ* Flushing

Surfactants are amphiphilic organic molecules that have both hydrophobic and hydrophilic moieties. When dissolved in water, surfactant molecules tend to cluster together and form **micelles** (Figure 9.40). These micelles aggregate when a specific threshold, known as critical micellar concentration (CMC), is exceeded. In water, the hydrophilic "heads" of the dissolved surfactant molecules point towards the aqueous phase, assuring that surfactants are highly water soluble. The hydrophobic "tails" of the surfactant molecule project inside the micelle. The "heads" and "tails" of surfactant molecules are typically separated by hydrocarbon chains. The non-polar core of these micelles attracts equally non-polar compounds, like TCE or other chlorinated solvents. This partitioning of hydrophobic contaminants into the micelle structure is the basis of the surfactant enhanced flushing technology, which is also referred to as Surfactant Enhanced Aquifer Remediation (SEAR). The enhancement of contaminant solubility is directly proportional to the concentration of the surfactant above the CMC.

Surfactants also reduce the interfacial tension between the aqueous and NAPL phases. At very low interfacial tensions, larger globules of NAPL spontaneously break

FIGURE 9.40 Surfactants are amphiphilic compounds; they have both hydrophobic and hydrophilic moieties. Above the critical micelle concentration, surfactant molecules aggregate into micelles. Hydrophobic contaminants (TCE shown here) can partition into the hydrophobic interior of the micelle.



up into tiny droplets of about 5 to 50 nm in radius. At that point, the system consists of water, NAPL droplets and surfactants and is called a **microemulsion**. The reduction in interfacial tension and formation of microemulsions can be exploited to **mobilize** NAPL. Relative to surfactant enhanced solubilization, NAPL mobilization can remove more contaminant mass in less time. But, in case of DNAPL, there is greater risk of uncontrolled downward movement, as DNAPL is being physically displaced by the surfactant solution. When injecting surfactant solution with the primary purpose of inducing mobilization, it is therefore necessary to prevent vertical DNAPL migration. This can either be achieved by having competent bedrock or a capillary barrier underlying the treatment zone or by manipulating the density the DNAPL, for example, by co-injection of cosolvents. Because of the risk of vertical displacement, mobilization flooding should only be considered when there is a high degree of certainty that the flushing solution can be recovered. In general, a surfactant flushing system can be tailored to remove contaminants either primarily by solubilization or primarily by mobilization (Pope 2015). Under appropriate site conditions, removal rates as high as 98.5% of the original DNAPL mass have been reported (Londergan et al. 1997). A number of very well documented field tests have demonstrated that *in situ* flushing can achieve these high removal percentages in months, and sometimes even days (EPA 2000).

Surfactants are produced at industrial scales and are one of the most widely used chemicals. Many different kinds of surfactants have been developed for a large number of applications, including detergents, fire-fighting agents (see Chap. 5) or pharmaceuticals and cosmetics. Depending on the charge of their polar heads, surfactant can be non-ionic., cationic or anionic. For most remediation applications, non-ionic or anionic surfactants are preferred because they do not sorb as strongly to the charged surfaces of natural minerals (i.e., clays) as cationic surfactants. Also, they are generally less toxic than cationic surfactants.

Case Study: Hill Air Force Base, Utah.

The Hill Air Force Base is located near Ogden, Utah, USA. The test site was used continuously from 1967 until 1975 for base-wide disposal of spent degreasing fluids and other solvents. At the site, DNAPL pooled within the topographic lows of a clay aquitard approximately 15 to 17 m (50 to 56 ft) below ground surface. The DNAPL was composed of approximately 70% TCE, 10% PCE, 5% TCA with other minor volatile organic constituents. In addition, there was a significant oil and grease fraction entrained in the DNAPL. The groundwater contaminants included PCE, TCE, TCA, DCE and trace heavy metals. The depth to groundwater was 8.3 m (27 ft). The unconfined aquifer consists of alluvial sands and gravel. The deposits are highly heterogeneous and are underlain by a thick uniform and continuous clay layer. The effective porosity of the aquifer is 20% and its hydraulic conductivity is 6×10^{-3} to 5×10^{-2} cm/sec (17 ft/day to 146 ft/day).

Prior to the surfactant flooding, a DNAPL source-recovery system was installed. Partitioning interwell tracer tests (PITT) were conducted pre- and post- surfactant flooding to characterize the DNAPL distribution and to demonstrate the removal efficiency of the surfactant treatment. The flushing solution injected into the treatment zone consisted of 8% an anionic surfactant (Aerosol MA-801) and 4% isopropyl alcohol. About 0.7% of sodium chloride was added to adjust the ionic strength of the mixture. The solution decreased the interfacial tension between the surfactant solution and the DNAPL to 0.02 dynes/cm. About 2.4 pore volumes of the flushing solution were injected during a 3 day period, followed by 5.5 days compounds by self-sustaining smoldering processes (Switzer et al. 2009; Pironi et al. 2009). This approach is commercialized as self-sustaining treatment for active remediation (STAR) technology.

ISTT field applications are growing in number, partially because clean up goals can be achieved quickly, often within days or weeks. ESTCP (2010) provides a critical evaluation of 182 ISTT applications conducted between 1988 and 2007. Of those 182 applications, 87 used electrical resistance heating, 46 steam-based heating, 26 conductive heating, and 23 other heating technology applications. Measured in terms of reducing contaminant concentration and mass flux from the treatment zone, improvements ranged from less than 10 to over 1000 times. Overall, the electrical resistance heating and thermal conductive heating variants of ISTT are less affected by heterogeneous and low-permeability lithologies (EPA 2014a), which is why *in situ* thermal technology performance appears less hindered by the geologic stratification and mass-transfer resistances that limit other *in situ* remediation technologies (Triplett Kingston, Dahlen, and Johnson 2010).

9.15 *In situ* Chemical Oxidation (ISCO)

In situ chemical oxidation (ISCO) refers to a groundwater remediation technology that relies on the chemical oxidation of a wide variety of dissolved contaminants by strong oxidants, such as permanganate (MnO_4^-), hydrogen peroxide (H_2O_2), ozone (O_3), catalyzed hydrogen peroxide (Fenton oxidation), persulfate ($S_2O_8^{2-}$), peroxone (H_2O_2 and O_3), or percarbonate. The reactive species and other properties of common oxidants are summarized in Table 9.4. Relative to each other, ozone and persulfate are stronger oxidants than permanganate and hydrogen peroxide. Fenton's reagent produces a variety of oxidizing species of different strengths.

An ISCO treatment system is similar to *in situ* enhanced flushing systems, except that generally no extraction well(s) is required. A solution of the oxidant in water is prepared on the site and then injected into the subsurface. Vertical injection wells and direct push probes are the most common delivery methods. As the oxidant solution moves through the treatment zone it comes into contact with the contaminant and degrades it into benign compounds, including carbon dioxide and water. The oxidant concentration and the amount of oxidant mass injected into the treatment zone must be determined beforehand based on the initial soil and groundwater contaminant concentrations. Also, natural organic matter (NOM) or reduced minerals, carbonate, and other free radical scavengers in the subsurface can reduce the amount of oxidant available to degrade the target compounds. Thus, the amount of ISCO reagent that can be potentially wasted on oxidant consuming compounds must be included into the oxidant dose calculations. This **natural oxidant demand** is an important ISCO design parameter and failure to consider it will influence the treatment performance and cost of the ISCO system. However, there is little advantage in an "over injection of oxidant" approach because there is the potential to enhance the release and migration of the target contaminants, generate excessive heat, and form undesired by-products, including precipitates (NRC 2005b; IRTC 2005; Siegrist et al. 2011).

Oxidizing agents like sodium or potassium permanganate, persulfate and percarbonate are solids, whereas hydrogen peroxide is a liquid and ozone is a gas. Because

TABLE 9.4 Common oxidants and their most important oxidant reactions, including persistence and electrode potentials of the reactive species involved. Reduction potential is negative.

Oxidant	Reactive Species	Reactions	Persistence[+]	Electrode Potential (Eh)
Permanganate	Permanganate ion (MnO_4^-)	$MnO_4^- + 4H^+ + 3e^- \rightarrow MnO_{2(solid)} + 2H_2O$ ($3.5 < pH < 12$)	>3 months	1.7 V
Hydrogen peroxide	Hydrogen peroxide (H_2O_2)	$H_2O_2 + 2H^+ + 2e^- \rightarrow 2H_2O$	min.-hrs	1.8 V
Ozone	Ozone (O_3)	$O_3 + 2H^+ + 2e^- \rightarrow O_2 + 2H_2O$	min.-hrs	2.1 V
	Hydroxyl radical (•OH)	$2O_3 + 3H_2O \rightarrow 4O_2 + 2\cdot OH + 2H_2O$		2.8 V
Fenton's (catalyzed hydrogen peroxide)		$Fe_2^+ + H_2O_2 \rightarrow Fe^{3+} + \cdot OH + OH^-$ (initiation rxn)		
	Hydroxyl radical (•OH)	$2\cdot OH + 2H^+ + 2e^- \rightarrow 2H_2O$		2.8
	Perhydroxyl radical (•OH_2)	$\cdot OH_2 + 2H^+ + 2e^- \rightarrow 2H_2O$		1.7
	Superoxide radical (•O_2)	$\cdot O_2 + 4H^+ + 3e^- \rightarrow 2H_2O$		–2.4 V
	Hydroperoxide anion (HO_2^-)	$HO_2^- + H_2O + 2e^- \rightarrow 3OH^-$		–0.9 V
Persulfate ($S_2O_8^{2-}$)	Persulfate ($S_2O_8^{2-}$)	$S_2O_8^{2-} + 2e^- \rightarrow 2\cdot SO_4^{2-}$ (initiation rxn)	hrs-weeks	2.1 V
	Sulfate radical (•SO_4^-)	$\cdot SO_4^- + e^- \rightarrow SO_4^{2-}$		2.6 V
Activated Persulfate ($S_2O_8^{2-}$)		$S_2O_8^{2-}$ + Heat* $\rightarrow 2\cdot SO_4^-$ (initiation rxn)	min-weeks	2.1 V
	Sulfate radical (•SO_4^-)	$2\cdot SO_4^- + 2H_2O \rightarrow 2HSO_4^- + 2\cdot OH$		2.6 V
	Hydroxyl radical (•OH)	$2\cdot OH + 2H^+ + 2e^- \rightarrow 2H_2O$		2.8 V

[+] Literature values and estimates.

* Other persulfate activators: Fe^{2+}, elevated pH >10.5 and peroxone (H_2O_2 and O_3).

Source: Huling and Pivetz (2006); ITRC 2005b.

ozone is inherently unstable, it must be produced at the site immediately before injection into subsurface. Permanganate salts might be delivered to the site in form of an aqueous solution. Most oxidants are hazardous chemicals that must be handled properly by trained field personnel.

ISCO treatment is applicable to variety of contaminants; however, chlorinated solvents are by far the most commonly treated ones. In an analysis of ISCO field applications and performance data, Krembs et al. (2010) found that of 223 sites analyzed, 70% treated chloroethenes and 8% chloroethanes. Other commonly treated contaminants include chlorobenzenes, BTEX and other petroleum hydrocarbons, incl. PAH and gasoline additives (MTBE). About 54% of sites contained NAPL. In general, fuel-related compounds, particularly MTBE, can be treated more effectively relative to chlorinated compounds. However, a number of organic compounds (e.g., PCB or perfluorinated flame retardants) are resistant or even impossible to treat with currently existing ISCO methods. Therefore, the development of advanced oxidation processes is an area of ongoing research.

ISCO is a comparably aggressive contaminant mass-reduction technology and primarily applied to NAPL source zones and groundwater plumes with high dissolved contaminant concentrations. ISCO has been implemented at sites with varied subsurface conditions, ranging from unconsolidated permeable and homogeneous materials to fractured bedrock environments. Generally, ISCO is a relative rapid treatment process that can achieve treatment goals within weeks or months. However, a comparably small percentage of ISCO treatments met pre-defined remediation goals, such as maximum contaminant levels (MCL) (Krembs et al. 2010). This may signify that remediation practitioners overestimated the performance of ISCO or underestimated the impact of site conditions on this technology.

Of the ISCO projects reviewed by Krembs et al. (2010), 89% combined the use of ISCO with other *in situ* remediation technologies. For instance, ISCO has been coupled with surfactants/cosolvents enhanced DNAPL removal, either in sequence or simultaneously (Dugan et al. 2010). Similarly, Eberle et al. (2017) reports on a pilot-scale field project where activated persulfate oxidant was used in combination with cyclodextrin, an enhanced solubilization agent discussed in Section 9.12. The advantage of combining the two treatment approaches is that the enhanced solubilization agent increases the mass of contaminant in solution and thereby makes it available for destruction by the oxidizing agent. This *in situ* "treatment train" approach, when performed as designed, can eliminate the need for extracting and *ex situ* treatment of contaminated liquids. Also, there is ample field site evidence that microbial populations are not permanently reduced by ISCO. In fact, it appears that microbial populations even flourish after ISCO treatment, which permits coupling ISCO with enhanced bioremediation or monitored natural attenuation (MNA) technologies (NRC 2005).

9.16 Phytoremediation

Phytoremediation is a set of technologies that rely on plants and their associated microorganisms to sequester, extract, or degrade toxic compounds in groundwater, soils, sediment and surface water. Because it is a natural process, phytoremediation can be an effective remediation method for a variety of sites and contaminants, at a reduced rate. A large number of plants have been evaluated for potential use in phytoremediation applications. The selection of one or more plant species is based on factors such as ability to extract or degrade the contaminants of concern, adaptation to local climates, high biomass, depth root structure, compatibility with soils, growth rate, ease of planting and maintenance, and ability to take up large quantities of water through the roots (U.S. EPA 2012c). Recent developments in transgenic plant research may lead to a greater selection of plant varieties or the treatment of contaminants currently not possible (Lee 2013). The duration of the treatment generally depends on the type and initial contaminant concentration, its distribution within the treatment zone, plant selection and their growth rate, hydrogeologic and climatologic conditions, and other site characteristics.

Phytoremediation has become an alternative to other, more aggressive cleanup technologies because of relatively low capital costs and the inherently aesthetic nature of planted sites. However, this treatment technology is not a "Do something quick and cheap in the field and then walk away" approach. Like any remediation system, phytoremediation requires significant operation, maintenance, and monitoring for several years after planting. For instance, plants may require irrigation, fertilization, weed and pest control or replanting (ITRC 2009).

■ 9.17 Summary

There is great interest in developing effective and efficient methods of remediating contaminated soils and groundwater in order to meet the mandates of public concern and federal legislation such as RCRA and CERCLA in the United States.

In order to have a successful remediation, it is necessary to first isolate or remove the source of the contamination. Sources can include hazardous wastes spread on the land or improperly buried in the earth, leaking landfills, leaking underground storage tanks, or soils that have become contaminated by accidental spills and leaks. If it is not possible to remove sources, they can be isolated by physical barriers, such as slurry walls and impermeable covers or by hydrodynamic barriers created by pumping and injection wells.

While not very effective, contaminated groundwater can be pumped from the ground and treated. Pump-and-treat technologies can be effectively used to hydraulically control plumes. Before initiating a pump-and-treat program, any mobile NAPL present should be removed. Floating NAPLs can be removed by multi-phase extraction pumps located in wells. Residual NAPL and contaminants sorbed onto mineral surfaces and soil organic carbon will slowly partition into the clean groundwater that replaces the contaminated groundwater removed by pumping. This will greatly prolong the period of time that it takes to remediate the aquifer. If all the residual contamination is not removed from the aquifer, the concentration of contaminants will increase after the termination of a pump-and-treat operation. It may be impossible to remediate sites contaminated with DNAPLs by conventional pump-and-treat methods. Such aquifers might require permanent plume-stabilization wells to prevent the spread of the plume, or need to be remediated with more advanced technologies.

Water that is extracted from the aquifer can be treated to remove both organic and inorganic contaminants. Methods of treatment of dissolved organics include air stripping and carbon absorption. Underground tanks that are leaking should be removed and replaced. Soil and groundwater remediation is frequently necessary after a leaking tank has been removed.

Vadose zone soil contaminated by residual volatile organic compounds (VOC) can be remediated by soilvapor extraction systems. Air, containing organic vapors, is drawn from the soil pores via SVE wells in the vadose zone and replaced with fresh air. Some methods exist that combine pumping water for treatment with soil vapor extraction to treat contaminated soil and groundwater simultaneously.

Soil and groundwater contaminated by organic compounds may be amenable to bioremediation by both aerobic and anaerobic microbes. Electron acceptors and/or donor may be added to the soil or aquifer to encourage microbial activity. *In situ* bioremediation and related monitored natural attenuation (MNA) processes have the advantage of treating the contaminants dissolved in soil and groundwater at the same time as residual contaminants in the soil.

Permeable Reactive Barriers (PRB) are linear structures placed in the path of an advancing groundwater plume. Reactive materials inside the PRB, such as metallic iron, interact with the dissolved contaminants and degrade or immobilize them. PRBs are passive treatment systems because no pumping is required.

Chemically-enhanced *in situ* flushing technology relies on chemicals that enhance the solubility and, in some case, mobility of NAPL compounds in the subsurface. The primary objective of this remediation technology is to remove the maximum amount of contaminant with a minimum amount of chemicals and in minimal time while maintaining hydraulic control over the injected chemicals and contaminant. This approach requires injection and extraction wells with above ground treatment of the extracted liquids.

During thermal *in situ* treatment, heat is delivered to the treatment zone to volatize, displace, or destroy amendable contaminants in the subsurface. Convection and conduction heat sources have been tested and found effective for remediating a variety of contaminants, including some that are not treatable with other methods. However, high temperature necessary to destroy those compounds can also affect the soil properties. Thermal treatment is typically combined with SVE systems to capture volatilized compounds. New approaches include subsurface controlled, contaminant burning, or smoldering techniques.

In situ oxidation relies on strong oxidants that, when injected into the treatment zone, degrade organic contaminants. This aggressive remediation approach typically does not require the extraction of contaminated liquids from the subsurface and is applicable to a large number of organic compounds.

Phytoremediation takes advantage of green plants and their ability to take up, transform or volatilize a number of metal and organic contaminants. While limited to relatively low soil and groundwater contaminant concentrations, and typically requiring many growing seasons to achieve clean up goals, phytoremediation is a green technology.

While great advances have been made in the field of remediation over the past decades, many contaminants and site-settings, particularly fractured bedrock aquifers, remain difficult or impossible to treat with current methods. Hence, this topic will remain an area of active research for many years.

Chapter Notation

B	Uniform thickness of a confined aquifer
Bgs	Below ground surface
C	Concentration
Co	Initial concentration
U	Regional specific discharge (Darcy velocity)
Q	Pumping rate of plume-capture well
d	Distance between extraction wells
k	Pseudo-first order rate contestant
x	Distance along the x axis
y	Distance along the y axis
$h_0—h$	Drawdown
T	Aquifer transmissivity
S	Aquifer storativity
R	Radius of a pumping well
t	Time since pumping began

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DOCUMENT

9

TITLE 35: ENVIRONMENTAL PROTECTION
SUBTITLE G: WASTE DISPOSAL
CHAPTER I: POLLUTION CONTROL BOARD
SUBCHAPTER j: COAL COMBUSTION WASTE SURFACE IMPOUNDMENTS

PART 845
STANDARDS FOR THE DISPOSAL OF COAL COMBUSTION RESIDUALS IN SURFACE IMPOUNDMENTS

SUBPART A: GENERAL PROVISIONS

SUBPART B: PERMITTING

SUBPART C: LOCATION RESTRICTIONS

SUBPART D: DESIGN CRITERIA

SUBPART E: OPERATING CRITERIA

SUBPART F: GROUNDWATER MONITORING AND CORRECTIVE ACTION

SUBPART G: CLOSURE AND POST-CLOSURE CARE

SUBPART H: RECORDKEEPING

SUBPART I: FINANCIAL ASSURANCE

AUTHORITY: Implementing Sections 12, 22, and 22.59 of the Environmental Protection Act [415 ILCS 5/12, 22, and 22.59] and authorized by Sections 22.59, 27, and 28 of the Environmental Protection Act [415 ILCS 5/22.59, 27, and 28].

SOURCE: Adopted in R20-19 at 45 Ill. Reg. 5884, effective April 21, 2021.

SUBPART A: GENERAL PROVISIONS

Section 845.100 Scope and Purpose

a) This Part establishes criteria for determining which CCR surface impoundments do not pose a reasonable probability of adverse effects on health or the environment. CCR surface impoundments failing to satisfy any of the requirements of this Part are considered open dumps, which are prohibited under Section 21(a) of the Act.

b) This Part applies to owners and operators of new and existing CCR surface impoundments, including any lateral expansions of CCR surface impoundments that dispose of or otherwise engage in solid waste management of CCR generated from the combustion of coal at electric utilities and independent power producers. Unless otherwise provided in this Part, these requirements also apply to CCR surface impoundments located off-site of the electric utility or independent power producer.

c) This Part also applies to inactive CCR surface impoundments at active and inactive electric utilities or independent power producers, regardless of the fuel currently used at the facility to produce electricity.

d) Except as provided in Section 845.170, inactive CCR surface impoundments are subject to all the requirements of this Part applicable to existing CCR surface impoundments.

e) This Part does not apply to wastes, including fly ash, bottom ash, boiler slag, and flue gas desulfurization materials generated at facilities that are not part of an electric utility or independent power producer, such as manufacturing facilities, universities, and hospitals. This Part also does not apply to fly ash, bottom ash, boiler slag, and flue gas desulfurization materials generated primarily from the combustion of fuels (including other fossil fuels) other than coal, for the purpose of generating electricity unless the fuel burned consists of more than 50% coal on a total heat input or mass input basis, whichever results in the greater mass feed rate of coal.

f) This Part does not apply to the beneficial use of CCR.

g) This Part does not apply to CCR placement at active or abandoned underground or surface coal mines.

h) This Part does not apply to landfills that receive CCR.

i) If a CCR surface impoundment has completed an Agency-approved closure before April 21, 2021, this Part does not require the owner or operator of the CCR surface impoundment to resubmit to the Agency any closure plan, closure report, or closure certification for that completed closure.

j) Upon completion of an Agency-approved closure, the CCR surface impoundment is considered a CCR surface impoundment that has completed closure for purposes of fee applicability under Section 22.59(j) of the Act.

Section 845.110 Applicability of Other Regulations

a) Compliance with the requirements of this Part does not affect the need for the owner or operator of a CCR surface impoundment, or lateral expansion of a CCR surface impoundment, to comply with all other applicable federal, state, tribal, or local laws or other requirements.

b) Any CCR surface impoundment or lateral expansion of a CCR surface impoundment is subject to the following requirements:

   1) Illinois Endangered Species Protection Act [520 ILCS 10] and 40 CFR 257.3-2.

2) Surface Water

A) A facility must not cause a discharge of pollutants into waters of the United States that is in violation of the requirements of the National Pollutant Discharge Elimination System (NPDES) under section 402 of the Clean Water Act.

B) A facility must not cause a discharge of dredged material or fill material to waters of the United States that is in violation of the requirements under section 404 of the Clean Water Act, as amended.

C) A facility or practice must not cause non-point source pollution of waters of the United States that violates applicable legal requirements implementing an areawide or statewide water quality management plan that has been approved by USEPA under section 208 of the Clean Water Act, as amended.

D) Definitions of the terms "discharge of dredged material", "point source", "pollutant", and "waters of the United States" can be found in the Clean Water Act, as amended (33 USC 1251 et seq.) and implementing regulations, specifically 33 CFR 323 (42 FR 37122, July 19, 1977).

E) Except as in compliance with the provisions of the Act, Board regulations, and the CWA, and the provisions and conditions of the NPDES permit issued to the discharger, the discharge of any contaminant or pollutant by any facility into the waters of the State from a point source or into a well will be unlawful.

3) Rivers, Lakes and Streams Act [615 ILCS 5/23 and 23(a)] and 17 Ill. Adm. Code 3702.

Section 845.120 Definitions

Except as stated in this Section, or unless a different meaning of a word or term is clear from the context, the definition of words or terms in this Part will be the same as that applied to the same words or terms in the Environmental Protection Act:

"1000-year flood" means a flood of magnitude (or greater) of 1 in 1000 probability of occurring in any given year.

"Act" means the Illinois Environmental Protection Act [415 ILCS 5].

"Active facility" or "active electric utility" or "independent power producer" means any facility, subject to the requirements of this Part, that is in operation on or after October 19, 2015. An electric utility or independent power producer is in operation if it is generating electricity that is provided to electric power transmission systems or to electric power distribution systems on or after October 19, 2015. An off-site CCR surface impoundment is in operation if it is accepting or managing CCR on or after October 19, 2015.

"Active life" or "in operation" means the period of operation beginning with the initial placement of CCR in the CCR surface impoundment and ending at completion of closure activities in accordance with Subpart G.

"Agency" means the Illinois Environmental Protection Agency.
"Aquifer" means a geologic formation, group of formations, or portion of a formation capable of yielding usable quantities of groundwater to wells or springs.

"Area-capacity curves" means graphic curves that readily show the reservoir water surface area, in acres, at different elevations from the bottom of the reservoir to the maximum water surface, and the capacity or volume, in acre-feet, of the water contained in the reservoir at various elevations.

"Areas susceptible to mass movement" means those areas of influence (i.e., areas characterized as having an active or substantial possibility of mass movement) where, because of natural or human-induced events, the movement of earthen material at, beneath, or adjacent to the CCR surface impoundment may result in the downslope transport of soil and rock material by means of gravitational influence. Areas of mass movement include, but are not limited to, landslides, avalanches, debris slides and flows, soil fluctuation, block sliding, and rock fall.

"Beneficial use of CCR" means CCR that meets the definition of "coal combustion by-product" in Section 3.135 of the Act [415 ILCS 5/3.135] and the definition of "beneficial use of CCR" in 40 CFR 257.53, incorporated by reference in Section 845.150.

"Board" means Illinois Pollution Control Board.

"Certified laboratory" means any laboratory certified under Section 4(o) of the Act or certified by USEPA for the specific constituents to be examined.

"Closed" for purposes of this Part means placement of CCR in a CCR surface impoundment has stopped, and the owner or operator has completed closure of the CCR surface impoundment and has initiated post-closure care in accordance with Subpart G.

"*Coal combustion residuals*" or "*CCR*" *means fly ash, bottom ash, boiler slag, and flue gas desulfurization materials generated from burning coal for the purpose of generating electricity by electric utilities and independent power producers*. [415 ILCS 5/3.142]

"CCR fugitive dust" means solid airborne particulate matter that contains or is derived from CCR, emitted from any source other than a stack or chimney.

"CCR storage pile" means any temporary accumulation of solid, non-flowing CCR placed on the land that is designed and managed to control releases of CCR to the environment. CCR contained in an enclosed structure is not a CCR storage pile. Examples of control measures to control releases from CCR storage piles include: periodic wetting, application of surfactants, tarps, or wind barriers to suppress dust; tarps or berms for preventing contact with precipitation and controlling run-on/run-off; and impervious storage pads or geomembrane liners for soil and groundwater protection.

"*CCR surface impoundment*" or "*impoundment*" *means a natural topographic depression, man-made excavation, or diked area, which is designed to hold an accumulation of CCR and liquids, and the surface impoundment treats, stores, or disposes of CCR.* [415 ILCS 5/3.143]

"Dike" means an embankment, berm, or ridge of either natural or man-made materials used to prevent the movement of liquids, sludges, solids, or other materials.

"Displacement" means the relative movement of any two sides of a fault measured in any direction.

"Disposal" means the discharge, deposit, injection, dumping, spilling, leaking, or placing of any solid waste as defined in section 1004(27) of the Resource Conservation and Recovery Act into or on any land or water or into any well so that the solid waste, or constituent thereof, may enter the environment or be emitted into the air or discharged into any waters, including groundwater. For purposes of this Part, disposal does not include the beneficial use of CCR.

"Downstream toe" means the junction of the downstream slope or face of the CCR surface impoundment with the ground surface.

"Enclosed structure" means:

> A completely enclosed, self-supporting structure that is designed and constructed of manmade materials of sufficient strength and thickness to support itself, the CCR, and any personnel and heavy equipment that operate within the structure, and to prevent failure due to settlement, compression, or uplift; climatic conditions; and the stresses of daily operation, including the movement of heavy equipment within the structure and contact of that equipment with containment walls;
>
> The structure has containment walls that are designed to be sufficiently durable to withstand any movement of personnel, CCR, and handling equipment within the structure;

> The structure is designed and operated to ensure containment and prevent fugitive dust emissions from openings, such as doors, windows and vents, and the tracking of CCR from the structure by personnel or equipment.

"Exceedance of the groundwater protection standard" means:

> For existing CCR surface impoundments and inactive CCR surface impoundments:
>
> an analytical result with a concentration greater than the numerical value of the constituents listed in Section 845.600(a), in a down gradient well; or
>
> when the up gradient background concentration of a constituent exceeds the numerical value listed in Section 845.600(a), an analytical result with a concentration at a statistically significant level above the up gradient background concentration, in a down gradient well.
>
> For new CCR surface impoundments and lateral expansions of existing CCR surface impoundments, an analytical result with a constituent concentration at a statistically significant level above the up gradient background concentration, in a down gradient well.

"Existing CCR surface impoundment" means a CCR surface impoundment in which CCR is placed both before and after October 19, 2015, or for which construction started before October 19, 2015 and in which CCR is placed on or after October 19, 2015. A CCR surface impoundment has started construction if the owner or operator has obtained the federal, State, and local approvals or permits necessary to begin physical construction and a continuous on-site, physical construction program had begun before October 19, 2015.

"Facility" means all contiguous land, and structures, other appurtenances, and improvements on the land, used for treating, storing, disposing of, or otherwise conducting solid waste management of CCR. A facility may consist of several treatment, storage, or disposal operational units (e.g., one or more landfills, surface impoundments, or combinations of them).

"Factor of safety" or "safety factor" means the ratio of the forces tending to resist the failure of a structure to the forces tending to cause that failure, as determined by accepted engineering practice.

"Fault" means a fracture or a zone of fractures in any material along which strata on one side have been displaced with respect to that on the other side.

"Flood hydrograph" means a graph showing, for a given point on a stream, the discharge, height, or other characteristic of a flood as a function of time.

"Free liquids" means liquids that readily separate from the solid portion of a waste under ambient temperature and pressure.

"Groundwater" means water below the land surface in a zone of saturation.

"Hazard potential classification" means the possible adverse incremental consequences that result from the release of water or stored contents due to failure of the diked CCR surface impoundment or mis-operation of the diked CCR surface impoundment or its appurtenances. The hazardous potential classifications include Class 1 and Class 2, defined as follows:

> Class 1 CCR surface impoundment means a diked surface impoundment where failure or mis-operation will probably cause loss of human life.
>
> Class 2 CCR surface impoundment means a diked surface impoundment where failure or mis-operation results in no probable loss of human life, but can cause economic loss, environmental damage, disruption of lifeline facilities, or impact other concerns.

"Height" means the vertical measurement from the downstream toe of the CCR surface impoundment at its lowest point to the lowest elevation of the crest of the CCR surface impoundment, not including spillways.

"Holocene" means the most recent epoch of the Quaternary period, extending from the end of the Pleistocene Epoch, at 11,700 years before present, to present.

"Hydraulic conductivity" means the rate at which water can move through a permeable medium (i.e., the coefficient of permeability).

"Inactive CCR surface impoundment" means a CCR surface impoundment in which CCR was placed before but not after October 19, 2015 and still contains CCR on or after October 19, 2015. Inactive CCR surface impoundments may be located at an active facility or inactive facility.

"Inactive Closed CCR surface impoundment" means an inactive CCR surface impoundment that completed closure before October 19, 2015 with an Agency-approved closure plan.

"Inactive facility" or "inactive electric utilities or independent power producers" means any facility that is not in operation on or after October 19, 2015.

"Incised CCR surface impoundment" means a CCR surface impoundment that is constructed by excavating entirely below the natural ground surface, holds an accumulation of CCR entirely below the adjacent natural ground surface, and does not consist of any constructed diked portion.

"Inflow design flood" means the flood hydrograph that is used in the design or modification of the CCR surface impoundment and its appurtenant works.

"In operation" means the same as "active life".

"Karst terrain" means an area where karst topography, with its characteristic erosional surface and subterranean features, is developed as the result of dissolution of limestone, dolomite, or other soluble rock. Characteristic physiographic features present in karst terrains include, but are not limited to, dolines, collapsed shafts (sinkholes), sinking streams, caves, seeps, large springs, and blind valleys.

"Lateral expansion" means a horizontal or vertical expansion of the waste boundaries of an existing CCR surface impoundment made after October 19, 2015.

"Liquefaction factor of safety" means the factor of safety (safety factor) determined using analysis under liquefaction conditions.

"Lithified earth material" means all rock, including all naturally occurring and naturally formed aggregates or masses of minerals or small particles of older rock that formed by crystallization of magma or by induration of loose sediments. This term does not include man-made materials, such as fill, concrete, and asphalt, or unconsolidated earth materials, soil, or regolith lying at or near the earth surface.

"Maximum horizontal acceleration in lithified earth material" means the maximum expected horizontal acceleration at the ground surface as depicted on a seismic hazard map, with a 98% or greater probability that the acceleration will not be exceeded in 50 years, or the maximum expected horizontal acceleration based on a site-specific seismic risk assessment.

"New CCR surface impoundment" means a CCR surface impoundment or lateral expansion of an existing or new CCR surface impoundment that first receives CCR or starts construction after October 19, 2015. A new CCR surface impoundment has started construction if the owner or operator has obtained the federal, State, and local approvals or permits necessary to begin physical construction and a continuous on-site, physical construction program had begun after October 19, 2015.

"Operator" means the person or persons responsible for the overall operation of a CCR surface impoundment.

"Outermost damage zone of a fault" means the volume of deformed wall rocks around a fault surface that results from the initiation, propagation, interaction and build-up of slip along faults.

"Owner" means the person or persons who own a CCR surface impoundment or part of a CCR surface impoundment.

"Poor foundation conditions" means those areas where features exist which indicate that a natural or human-induced event may result in inadequate foundation support for the structural components of an existing or new CCR surface impoundment. For example, failure to maintain static and seismic factors of safety, as required in Section 845.460, would cause a poor foundation condition.

"Probable maximum flood" means the flood that may be expected from the most severe combination of critical meteorologic and hydrologic conditions that are reasonably possible in the drainage basin.

"Qualified person" means a person or persons trained to recognize specific appearances of structural weakness and other conditions that are disrupting, or have the potential to disrupt, the operation or safety of the CCR surface impoundment by visual observation and, if applicable, to monitor instrumentation.

"Qualified professional engineer" means an individual who is licensed under the Professional Engineering Practice Act of 1989 [225 ILCS 325] to practice one or more disciplines of engineering and who is qualified by education, technical knowledge and experience to complete the engineering analyses and make the specific technical certifications required under this Part.

"Recognized and generally accepted engineering practices" means engineering maintenance or operation activities based on established codes, widely accepted standards, published technical reports, or a practice widely recommended throughout the industry. These practices generally detail approved ways to perform specific engineering, inspection, or mechanical integrity activities.

"Retrofit" means to remove all CCR and contaminated soils and sediments from the CCR surface impoundment, and to ensure the surface impoundment complies with the requirements in Section 845.410.

"Run-off" means any rainwater, leachate, or other liquid that drains over land from any part of a CCR surface impoundment or lateral expansion of a CCR surface impoundment.

"Run-on" means any rainwater, leachate, or other liquid that drains over land onto any part of a CCR surface impoundment or lateral expansion of a CCR surface impoundment.

"Sand and gravel pit" or "quarry" means an excavation for the extraction of aggregate, minerals or metals. The term sand and gravel pit and/or quarry does not include subsurface or surface coal mines.

"Seismic factor of safety" means the factor of safety (safety factor) determined using analysis under earthquake conditions using the peak ground acceleration for a seismic event with a 2% probability of exceedance in 50 years, equivalent to a return period of approximately 2,500 years, based on the U.S. Geological Survey (USGS) seismic hazard maps for seismic events with this return period for the region where the CCR surface impoundment is located.

"Seismic impact zone" means an area having a 2% or greater probability that the maximum expected horizontal acceleration, expressed as a percentage of the earth's gravitational pull (g), will exceed 0.10 g in 50 years.

"Slope protection" means engineered or non-engineered measures installed on the upstream or downstream slope of the CCR surface impoundment to protect the slope against wave action or erosion, including rock riprap, wooden pile, concrete revetments, vegetated wave berms, concrete facing, gabions, geotextiles, or fascines.

"Solid waste management" or "management" means the systematic administration of the activities that provide for the collection, source separation, storage, transportation, processing, treatment, or disposal of solid waste.

"Static factor of safety" means the factor of safety (safety factor) determined using analysis under the long-term, maximum storage pool loading condition, the maximum surcharge pool loading condition, and the end-of-construction loading condition.

"Structural components" means liners, leachate collection and removal systems, final covers, run-on and run-off systems, inflow design flood control systems, and any other component used in the construction and operation of the CCR surface impoundment that is necessary to ensure the integrity of the surface impoundment and ensure that the contents of the surface impoundment are not released into the environment.

"Temporary accumulation" means an accumulation on the land that is neither permanent nor indefinite. To demonstrate that the accumulation on the land is temporary, all CCR must be removed from the pile at the site. The entity engaged in the activity must have a record in place, such as a contract, purchase order, facility operation and maintenance, or fugitive dust control plan, documenting that all the CCR in the pile will be completely removed according to a specific timeline.

"Unstable area" means a location that is susceptible to natural or human-induced events or forces capable of impairing the integrity of that area, including structural components of some or all the CCR surface impoundment that are responsible for preventing releases from the surface impoundment. Unstable areas can include poor foundation conditions, areas susceptible to mass movements, and karst terrains.

"Uppermost aquifer" means the geologic formation nearest the natural ground surface that is an aquifer, as well as lower aquifers that are hydraulically interconnected with this aquifer within the facility's property boundary. Upper limit is measured at a point nearest to the natural ground surface to which the aquifer rises during the wet season.

"Waste boundary" means a vertical surface located at the hydraulically downgradient limit of the CCR surface impoundment. The vertical surface extends down into the uppermost aquifer.

"Wetlands" means those areas that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas.

Section 845.130 Surface Impoundment Identification

The owner or operator of a CCR surface impoundment must place on, or immediately adjacent to, the CCR surface impoundment a permanent identification marker at least six feet high showing the identification number of the CCR surface impoundment assigned by the Agency, the name associated with the CCR surface impoundment and the name of the owner or operator of the CCR surface impoundment. The owner or operator must maintain the marker at all times an operating permit is required under this Part.

Section 845.140 Right of Inspection

The owner or operator of a CCR surface impoundment must allow the Agency and its duly authorized representatives to perform inspections in accordance with the Agency's authority under the Act, including:

a) Entering, at reasonable times, the facility where CCR surface impoundments are located or where any activity is to be conducted under a permit issued under this Part;

b) Having access to and copying at reasonable times any records required to be kept under the terms and conditions of a permit of this Part;

c) Inspecting at reasonable times, including during any hours of operation:

  1) Equipment constructed or operated under a permit issued under this Part;

  2) Equipment or monitoring methodology; or

  3) Equipment required to be kept, used, operated, calibrated and maintained under a permit issued under this Part;

d) Obtaining and removing, at reasonable times, samples of any raw or finished water, discharge or emission of pollutants;

e) Entering, at reasonable times, to use any photographic, recording, testing, monitoring or other equipment for the purpose of preserving, testing, monitoring or recording any raw or finished water, activity, discharge or emission authorized by a permit.

Section 845.150 Incorporations by Reference

a) For purposes of this Part, the Board incorporates the following material by reference:

1) Non-Regulatory Government Publications and Publications of Recognized Organizations and Associations:

Association for the Advancement of Cost Engineering (AACE), 726 East Park Avenue #180, Fairmont, WV 26554, (304) 296-8444, web.aacei.org.

"Cost Estimate Classification System — As Applied in Engineering, Procurement, and Construction for the Process Industries", TCM Framework: 7.3 – Cost Estimating and Budgeting. March 6, 2009, AACE International Recommended Practice No. 18R-97.

NTIS. National Technical Information Service, 5285 Port Royal Road, Springfield VA 22161, (703) 605-6000, www.ntis.gov.

"Test Methods for Evaluating Solid Waste, Physical/Chemical Methods", USEPA Publication No. SW-846, as amended by Updates I, II, IIA, IIB, III, IIIA, and IIIB (Doc. No. 955-001-00000-1) (available online at https://www.epa.gov/hw-sw846/sw-846-compendium).

2) Code of Federal Regulations, Available from the Superintendent of Documents, U.S. Government Publishing Office, Washington, DC 20401, (202) 783-3238, https://www.ecfr.gov, https:/www.govinfo.gov/app/collection/cfr, or https://www.federalregister.gov:

40 CFR 257.53 (2019) (Definition of “beneficial use of CCR”)

40 CFR 257.103(f)(1)(x) (85 Fed. Reg. 53563-64 (Aug. 28, 2020)) (Preparation of Semi-Annual Progress Reports)

b) This Section incorporates no later editions or amendments.

Section 845.160 Severability

If any provision of this Part or its application to any person or under any circumstances is adjudged invalid, that adjudication must not affect the validity of this Part as a whole or of any portion not adjudged invalid.

Section 845.170 Inactive Closed CCR Surface Impoundments

a) Among the provisions of this Part, only the following apply to inactive closed CCR surface impoundments:

  1) All of Subpart A: General Provisions;

  2) The following Sections of Subpart B (Permitting):

    A) Section 845.200;

    B) Section 845.210;

    C) Section 845.220(a), (c), and (f)(1);

    D) Section 845.230(c) and (d)(4);

    E) Section 845.250;

    F) Section 845.270;

    G) Section 845.280;

    H) Section 845.290;

  3) The following Section of Subpart G (Closure and Post-Closure Care): Section 845.780(b), (d), and (e); and

  4) All of Subpart I (Financial Assurance).

b) When a prior release from an inactive closed CCR surface impoundment has caused an exceedance of the groundwater quality standards in 35 Ill. Adm. Code 620, and the owner or operator has not completed remediation of the release before completing closure, the owner or operator must initiate or continue corrective action under an operating permit issued under this Part.

c) When a release from an inactive closed CCR surface impoundment causes an exceedance of the groundwater quality standards in 35 Ill. Adm. Code 620, and the Agency has not concurred with an alternative source demonstration, the owner or operator of an inactive closed CCR surface impoundment must initiate an assessment of corrective measures that prevents further releases, remediates any releases, and restores the affected area. The owner or operator of the inactive closed CCR surface impoundment must develop a corrective action plan and obtain a construction permit consistent with subsection (a)(2) before performing any corrective action to remediate any releases and to restore the affected area, including the final cover system, groundwater monitoring system, groundwater collection trench, extraction wells, slurry walls, or any construction related to corrective action.

SUBPART B: PERMITTING

Section 845.200 Permit Requirements and Standards of Issuance

a) Permit Requirements

1) No person may construct, install, or modify a CCR surface impoundment or related treatment or mitigation facilities, including corrective action measures under Subpart F, without a construction permit issued by the Agency under this Part.

2) Except as provided in Section 845.230(d), no person may operate a CCR surface impoundment without an operating permit issued by the Agency under this Part. For purposes of this Part, a CCR surface impoundment starts operation upon initial receipt of CCR.

3) No person may perform corrective action at a CCR surface impoundment without obtaining a construction permit for corrective action and modifying the facility's operating permit, or modifying the facility's operating permit when the approved corrective action does not require the modification of the CCR surface impoundment or the installation or modification of related treatment or mitigation facilities.

4) Except as provided in Section 22.59(e) of the Act, no person may close a CCR surface impoundment without obtaining a construction permit for closure issued by the Agency under this Part.

5) A CCR surface impoundment must maintain an operating permit until:

A) The completion of post-closure care when the CCR surface impoundment is closed with a final cover system; or

B) The completion of groundwater monitoring under Section 845.740(b) when the CCR surface impoundment is closed by removal.

6) The Agency may issue a joint construction and operating permit.

b) Standards for Issuance

1) Except as provided in subsection (b)(2), the Agency may not issue any construction or operating permit required by this Part unless the applicant submits adequate proof that the CCR surface impoundment will be constructed, modified or operated so as not to cause a violation of the Act or Board rules.

2) The existence of a violation of the Act, Board regulation, or Agency regulation will not prevent the issuance of a construction or operating permit under this Part if:

   A) The applicant has been granted a variance or an adjusted standard from the regulation by the Board;

   B) The permit application is for construction, installation, or operation of equipment to alleviate or correct a violation; or

   C) The permit application is for construction, installation, or operation of equipment necessary to restore, protect or enhance the environment.

3) *In granting permits, the Agency may impose reasonable conditions specifically related to the applicant's past compliance history with the Act as necessary to correct, detect, or prevent noncompliance. The Agency may impose such other conditions as may be necessary to accomplish the purpose of the Act and as are not inconsistent with this Part.* [415 ILCS 5/39(a)]

4) *In making its determinations on permit applications under this* Part*, the Agency may consider prior adjudications of noncompliance with the Act by the applicant that involved a release of a contaminant into the environment*. [415 ILCS 5/39(a)]

Section 845.210 General Provisions

a) All permit applications must be made on the forms prescribed by the Agency and must be mailed or delivered to the address designated by the Agency on the forms. The Agency must provide a dated, signed receipt upon request. The Agency's record of the date of filing must be deemed conclusive unless a contrary date is proved by a dated, signed receipt.

b) Required Signatures of Owners or Operators

   1) All permit applications must contain the name, address, email address and telephone number of the operator, or duly authorized agent, and the

property owner to whom all inquiries and correspondence must be addressed.

2) All permit applications must be signed by the owner, operator or a duly authorized agent of the operator.

3) An application submitted by a corporation must be signed by a principal executive officer of at least the level of vice president, or his or her duly authorized representative, if that representative is responsible for the overall operation of the facility described in the application form. In the case of a partnership or a sole proprietorship, the application must be signed by a general partner or the proprietor, respectively. In the case of a publicly owned facility, the application must be signed by either the principal executive officer, ranking elected official, or other duly authorized employee.

c) Legal Description. All permit applications must contain a legal description of the facility boundary and a description of the boundaries of all units included in the facility.

d) Previous Assessments, Investigations, Plans and Programs

1) The Agency may approve the use of any hydrogeologic site investigation or characterization, groundwater monitoring well or system, or groundwater monitoring plan, bearing the seal and signature of an Illinois Licensed Professional Geologist or Licensed Professional Engineer, completed before April 21, 2021 to satisfy the requirements of this Part.

2) For existing CCR surface impoundments, the owner or operator of the CCR surface impoundment may use a previously completed location restriction demonstration required by Section 845.300 (Placement Above the Uppermost Aquifer), Section 845.310 (Wetlands), Section 845.320 (Fault Areas), Section 845.330 (Seismic Impact Zones), and Section 845.340 (Unstable Areas) provided that the previously completed assessments meet the applicable requirements of those Sections.

3) For existing CCR surface impoundments, the owner or operator of the CCR surface impoundment may use a previously completed assessment to serve as the initial assessment required by Section 845.440 (Hazard Potential Classification Assessment), Section 845.450 (Structural Stability Assessment) and Section 845.460 (Safety Factor Assessment) provided that the previously completed assessment:

A) Was not completed more than five years ago; and

B) Meets the applicable requirements of those Sections.

4) For inactive closed CCR surface impoundments, the owner or operator of the CCR surface impoundment may use a post-closure care plan previously approved by the Agency.

e) The Agency must mail all notices of final action by certified mail, postmarked with a date stamp and with return receipt requested. Final action must be deemed to have taken place on the postmarked date that the notice is mailed.

f) Violation of any permit condition or failure to comply with the Act or regulations promulgated under the Act must be grounds for enforcement action as provided in the Act, including revocation of a permit.

g) Issuance of a permit under this Part does not relieve the applicant of the obligation to obtain other permits required by law.

h) The owner or operator must place in the facility's operating record all permit applications submitted to the Agency and all permits issued under this Part (see Section 845.800(d)(1)).

i) Agency Listserv

1) For each facility subject to this Part, the Agency must create and maintain a listserv. Each listserv must include the email addresses of all interested persons who notify the Agency in writing—either directly under subsection (i)(2) or through the facility owner or operator under Section 845.220(a)(9) or 845.240(f)(4)—of their respective email addresses and that they would like to receive emails of notices concerning the facility.

2) The Agency’s webpage must specify how interested persons may notify the Agency in writing of their respective email addresses and that they would like to be added to the Agency’s listserv for a facility subject to this Part.

3) When this Part requires that the Agency email a notice to the listserv for a facility, the Agency must do so within the timeframe specified, concurrently with other required means of disseminating the notice, or otherwise in a timely manner. When this Part requires an owner or operator to request that the Agency email a notice to the listserv for the facility, the Agency must do so within two business days after receiving the request from the owner or operator.

Section 845.220 Construction Permits

a) All construction permit applications must contain the following information and documents.

1) Design and Construction Plans (Construction History)

   A) Identifying Information

      i) The name and address of the person or persons owning or operating the CCR surface impoundment;

      ii) The name associated with the CCR surface impoundment; and

      iii) The identification number of the CCR surface impoundment if one has been assigned by the Agency.

   B) A statement of the purpose for which the CCR surface impoundment is being used, how long the CCR surface impoundment has been in operation, and the types of CCR that have been placed in the CCR surface impoundment.

   C) The name and size in acres of the watershed within which the CCR surface impoundment is located.

   D) A description of the physical and engineering properties of the foundation and abutment materials on which the CCR surface impoundment is constructed.

   E) A statement of the type, size, range, and physical and engineering properties of the materials used in constructing each zone or stage of the CCR surface impoundment; the method of site preparation and construction of each zone of the CCR surface impoundment; and the approximate dates of construction of each successive stage of construction of the CCR surface impoundment.

   F) At a scale that details engineering structures and appurtenances relevant to the design, construction, operation, and maintenance of the CCR surface impoundment, detailed dimensional drawings of the CCR surface impoundment, including a plan view and cross-sections of the length and width of the CCR surface impoundment, showing all zones, foundation improvements, drainage provisions, spillways, diversion ditches, outlets, instrument locations, and slope protection, in addition to the normal operating pool surface elevation and the maximum pool surface elevation following peak discharge from the inflow design flood, the expected maximum depth of CCR within the CCR surface impoundment, and any identifiable natural or manmade features that could adversely affect operation of the CCR surface impoundment due to malfunction or mis-operation.

G) A description of the type, purpose, and location of existing instrumentation.

H) Area-capacity curves for the CCR surface impoundment.

I) A description of each spillway and diversion design features and capacities and calculations used in their determination.

J) The construction specifications and provisions for surveillance, maintenance, and repair of the CCR surface impoundment.

K) Any record or knowledge of structural instability of the CCR surface impoundment.

2) Narrative Description of the Facility. The permit application must contain a written description of the facility with supporting documentation describing the procedures and plans that will be used at the facility to comply with the requirements of this Part. The descriptions must include, but are not limited to, the following information:

A) The types of CCR expected in the CCR surface impoundment, including a chemical analysis of each type of expected CCR;

B) An estimate of the maximum capacity of each surface impoundment in gallons or cubic yards;

C) The rate at which CCR and non-CCR waste streams currently enter the CCR surface impoundment in gallons per day and dry tons;

D) The estimated length of time the CCR surface impoundment will receive CCR and non-CCR waste streams; and

E) An on-site transportation plan that includes all existing and planned roads in the facility that will be used during the operation of the CCR surface impoundment.

3) Site Location Map. All permit applications must contain a site location map on the most recent United States Geological Survey (USGS) quadrangle of the area from the 7 ½ minute series (topographic), or on another map whose scale clearly shows the following information:

A) The facility boundaries and all adjacent property, extending at least 1000 meters (3280 feet) beyond the boundary of the facility;

B) All surface waters;

C) The prevailing wind direction;

D) The limits of all 100-year floodplains;

E) All-natural areas designated as a Dedicated Illinois Nature Preserve under the Illinois Natural Areas Preservation Act [525 ILCS 30];

F) All historic and archaeological sites designated by the National Historic Preservation Act (16 USC 470 et seq.) and the Illinois Historic Sites Advisory Council Act [20 ILCS 3410]; and

G) All areas identified as critical habitat under the Endangered Species Act of 1973 (16 USC 1531 et seq.) and the Illinois Endangered Species Protection Act [520 ILCS 10].

4) Site Plan Map. The application must contain maps, including cross-sectional maps of the site boundaries, showing the location of the facility. The following information must be shown:

A) The entire facility, including any proposed and all existing CCR surface impoundment locations;

B) The boundaries, both above and below ground level, of the facility and all CCR surface impoundments or landfills containing CCR included in the facility;

C) All existing and proposed groundwater monitoring wells; and

D) All main service corridors, transportation routes, and access roads to the facility.

5) A narrative description of the proposed construction of, or modification to, a CCR surface impoundment and any projected changes in the volume or nature of the CCR or non-CCR waste streams.

6) Plans and specifications fully describing the design, nature, function and interrelationship of each individual component of the facility.

7) A new groundwater monitoring program or any modification to an existing groundwater monitoring program that includes but is not limited to the following information:

        A) A hydrogeologic site investigation meeting the requirements of Section 845.620, if applicable;

        B) Design and construction plans of a groundwater monitoring system meeting the requirements of Section 845.630; and

        C) A proposed groundwater sampling and analysis program that includes selection of the statistical procedures to be used for evaluating groundwater monitoring data (see Sections 845.640 and 845.650).

    8) The signature and seal of a qualified professional engineer.

    9) Certification that the owner or operator of the CCR surface impoundment completed the public notification and public meetings required under Section 845.240, a summary of the issues raised by the public, a summary of any revisions, determinations, or other considerations made in response to those issues, and a list of interested persons in attendance who would like to be added to the Agency's listserv for the facility.

b) New Construction. In addition to the requirements in subsection (a), all construction permit applications to build a new CCR surface impoundment, lateral expansion of a CCR surface impoundment, or retrofit an existing CCR surface impoundment must also contain the following information and documents:

    1) Plans and specifications that demonstrate the proposed CCR surface impoundment will meet the location standards in the following Sections:

        A) Section 845.300 (Placement Above the Uppermost Aquifer);

        B) Section 845.310 (Wetlands);

        C) Section 845.320 (Fault Areas);

        D) Section 845.330 (Seismic Impact Zones); and

        E) Section 845.340 (Unstable Areas and Floodplains).

    2) Plans and specifications that demonstrate the proposed CCR surface impoundment will meet the following design criteria:

        A) The CCR surface impoundment will have a liner meeting the liner requirements of Section 845.400(b) or (c);

B) The CCR surface impoundment will have a leachate collection system meeting the requirements of Section 845.420; and

C) The CCR surface impoundment, if not incised, will be constructed with slope protection, as required by Section 845.430.

3) CCR fugitive dust control plan (see Section 845.500(b)).

4) Preliminary written closure plan (see Section 845.720(a)).

5) Initial written post-closure care plan, if applicable (see Section 845.780(d)).

c) Corrective Action Construction. In addition to the requirements in subsection (a), all construction permit applications that include any corrective action performed under Subpart F must also contain the following information and documents:

1) Corrective action plan (see Section 845.670);

2) Groundwater modeling, including:

A) The results of groundwater contaminant transport modeling and calculations showing how the corrective action will achieve compliance with the applicable groundwater standards;

B) All modeling inputs and assumptions;

C) Description of the fate and transport of contaminants with the selected corrective action over time; and

D) Capture zone modeling, if applicable;

3) Any necessary licenses and software needed to review and access both the models and the data contained within the models required by subsection (c)(2);

4) Corrective action groundwater monitoring program, including identification of revisions to the groundwater monitoring system for corrective action; and

5) Any interim measures necessary to reduce the contaminants leaching from the CCR surface impoundment, and/or potential exposures to human or ecological receptors, including an analysis of the factors specified in Section 845.680(a)(3).

d) Closure Construction. In addition to the requirements in subsection (a), all construction permit applications for closure of the CCR surface impoundment under Subpart G must contain the following information and documents:

  1) Closure prioritization category , if applicable (see Section 845.700(g));

  2) Final closure plan (see Section 845.720(b)), including the closure alternatives analysis required by Section 845.710;

  3) Groundwater modeling, including:

    A) The results of groundwater contaminant transport modeling and calculations showing how the closure will achieve compliance with the applicable groundwater standards;

    B) All modeling inputs and assumptions;

    C) Description of the fate and transport of contaminants, with the selected closure over time;

    D) Capture zone modeling, if applicable; and

    E) Any necessary licenses and software needed to review and access both the model and the data contained within the model.

  4) Proposed schedule to complete closure; and

  5) Post-closure care plan specified in Section 845.780(d), if applicable.

e) *Owners or operators of CCR surface impoundments who submitted a closure plan to the Agency before May 1, 2019, and who complete closure before July 30, 2021, shall not be required to obtain a construction permit for closure under subsection (d)*. [415 ILCS 5/22.59(e)]

f) A single construction permit application may be submitted for new construction, corrective action, and closure if the construction is related to the same multi-phased project. The permit application for a project with multiple phases must contain all information required by subsections (a), (b), (c), and (d), as applicable.

g) Duration of Construction Permits

  1) For any construction permit that is not for the closure or retrofit of the CCR surface impoundment, the construction permit must be issued for fixed terms not to exceed 3 years.

2) For any construction permit for the closure or retrofit of a CCR surface impoundment, the construction permit must be issued for an initial fixed term expiring within the timeframe approved by the Agency in the construction permit or five years, whichever is less. The Agency may renew a construction permit for closure or retrofit in two-year increments under Section 845.760(b).

Section 845.230 Operating Permits

The operating permit applications must contain the following information and documents:

a) Initial operating permit for a new CCR surface impoundment and any lateral expansion of a CCR surface impoundment.

1) A demonstration that the CCR surface impoundment, as built, meets the location standards in the following Sections:

A) Section 845.300 (Placement Above the Uppermost Aquifer);

B) Section 845.310 (Wetlands);

C) Section 845.320 (Fault Areas);

D) Section 845.330 (Seismic Impact Zones); and

E) Section 845.340 (Unstable Areas and Floodplains);

2) Certification from a qualified professional engineer that the composite liner, or if applicable, the alternative composite liner, has been constructed in accordance with the requirements of Section 845.400(b) or (c);

3) Certification from a qualified professional engineer that the leachate collection system has been constructed in accordance with the requirements of Section 845.420, if applicable;

4) Evidence that the permanent markers required by Section 845.130 have been installed;

5) Documentation that the CCR surface impoundment, if not incised, will be operated and maintained with one of the forms of slope protection specified in Section 845.430;

6) Initial hazard potential classification assessment and accompanying certification (see Section 845.440(a)(2));

7) Initial Emergency Action Plan and accompanying certification (see Section 845.520(e));

8) Initial structural stability assessment and accompanying certification (see Section 845.450(c));

9) Initial safety factor assessment and accompanying certification (see Section 845.460(b));

10) Fugitive dust control plan and accompanying certification (see Section 845.500(b)(7));

11) Initial inflow design flood control system plan and accompanying certification (see Section 845.510(c)(3));

12) Proposed groundwater monitoring program, including a minimum of eight independent samples for each background and downgradient well (see Section 840.650(b));

13) Preliminary written closure plan (see Section 845.720(a));

14) Initial written post-closure care plan, if applicable (see Section 845.780(d));

15) An analysis of the chemical constituents found within the CCR to be placed in the CCR surface impoundment;

16) An analysis of the chemical constituents of all waste streams, chemical additives, and sorbent materials entering or contained in the CCR surface impoundment; and

17) A certification that the owner or operator meets the financial assurance requirements of Subpart I.

b) Renewal Operating Permit

1) Documentation that the CCR surface impoundment, if not incised, is being operated and maintained with one of the forms of slope protection specified in Section 845.430;

2) Emergency Action Plan certification if the plan was amended (see Section 845.520);

3) Fugitive dust control plan certification if the plan was amended (see Section 845.500(b)(7));

4) Any significant changes to the design and construction plans compiled under subsection (d)(2)(A) or Section 845.220(a)(1);

5) A statement that the groundwater monitoring has been conducted under an Agency approved groundwater monitoring program;

6) Written preliminary closure plan, if amended (see Section 845.720(a)); and

7) Written post-closure care plan, if amended (see Section 845.780(d)).

c) Post-Closure Care Operating Permit

The owner or operator of a CCR surface impoundment conducting post-closure care under Section 845.780 must maintain an operating permit until the completion of post-closure care. Any changes to the post-closure care plan, groundwater monitoring system, groundwater sampling and analysis program, and groundwater monitoring program must be submitted to the Agency in an operating permit application.

d) Initial Operating Permit for Existing, Inactive and Inactive Closed CCR Surface Impoundments

1) The owner or operator of an existing, inactive or inactive closed CCR surface impoundment who has not completed post-closure care must submit an initial operating permit application to the Agency by October 31, 2021;

2) The initial operating permit application for existing or inactive CCR surface impoundments that have not completed an Agency approved closure before July 30, 2021, must contain the following information and documents on forms prescribed by the Agency:

A) The history of construction specified in Section 845.220(a)(1);

B) An analysis of the chemical constituents found within the CCR to be placed in the CCR surface impoundment;

C) An analysis of the chemical constituents of all waste streams, chemical additives and sorbent materials entering or contained in the CCR surface impoundment;

D) A demonstration that the CCR surface impoundment, as built, meets, or an explanation of how the CCR surface impoundments fails to meet, the location standards in the following Sections:

- i) Section 845.300 (Placement Above the Uppermost Aquifer);
- ii) Section 845.310 (Wetlands);
- iii) Section 845.320 (Fault Areas);
- iv) Section 845.330 (Seismic Impact Zones); and
- v) Section 845.340 (Unstable Areas);

E) Evidence that the permanent markers required by Section 845.130 have been installed;

F) Documentation that the CCR surface impoundment, if not incised, will be operated and maintained with one of the forms of slope protection specified in Section 845.430;

G) Initial Emergency Action Plan and accompanying certification (see Section 845.520(e));

H) Fugitive dust control plan and accompanying certification (see Section 845.500(b)(7));

I) Groundwater Monitoring Information:

- i) A hydrogeologic site characterization (see Section 845.620);
- ii) Design and construction plans of a groundwater monitoring system (see Section 845.630);
- iii) A groundwater sampling and analysis program that includes selection of the statistical procedures to be used for evaluating groundwater monitoring data (see Section 845.640); and
- iv) Proposed groundwater monitoring program that includes a minimum of eight independent samples for each background and downgradient well (see Section 845.650(b));

J) Preliminary written closure plan (see Section 845.720(a));

K) Initial written post-closure care plan, if applicable (see Section 845.780(d));

L) The certification required by Section 845.400(h), or a statement that the CCR surface impoundment does not have a liner that meets the requirements of Section 845.400(b) or (c);

M) History of known exceedances of the groundwater protection standards in Section 845.600, and any corrective action taken to remediate the groundwater;

N) A certification that the owner or operator meets the financial assurance requirements of Subpart I;

O) Hazard potential classification assessment and accompanying certification (see Section 845.440(a)(2));

P) Structural stability assessment and accompanying certification (see Section 845.450(c));

Q) Safety factor assessment and accompanying certification (see Section 845.460(b));

R) Inflow design flood control system plan and accompanying certification (see Section 845.510(c)(3));

S) Safety and health plan (see Section 845.530); and

T) For CCR surface impoundments required to close under 845.700, the proposed closure priority categorization required by Section 845.700(g).

3) The initial operating permit application for an existing or inactive CCR surface impoundment where an Agency approved closure has been completed before July 30, 2021, and where the impoundment is not an inactive closed CCR surface impoundment, must contain the following information and documents on forms prescribed by the Agency:

A) The history of construction specified in Section 845.220(a)(1);

B) Evidence that the permanent markers required by Section 845.130 have been installed;

C) Documentation that the CCR surface impoundment, if not incised, will be operated and maintained with one of the forms of slope protection specified in Section 845.430;

D) Emergency Action Plan certification (see Section 845.520(e));

E) Groundwater monitoring information:

i) A hydrogeologic site characterization meeting the requirements of Section 845.620;

ii) Design and construction plans of a groundwater monitoring system meeting the requirements of Section 845.630;

iii) A groundwater sampling and analysis program that includes selection of the statistical procedures to be used for evaluating groundwater monitoring data (see Section 845.640); and

iv) Proposed groundwater monitoring program that includes a minimum of eight independent samples for each background and downgradient well (see Section 845.650(b));

F) Written post-closure care plan, if applicable (see Section 845.780(d));

G) History of known exceedances of the groundwater protection standards in Section 845.600, and any corrective action plan taken to remediate the groundwater.

4) The initial operating permit application for inactive closed CCR surface impoundments must contain the following information:

A) Evidence that the permanent markers required by Section 845.130 have been installed;

B) Groundwater monitoring program;

C) Written post-closure care plan (see Section 845.780(d)); and

D) History of known exceedances of the groundwater quality standards in 35 Ill. Adm. Code 620, whether the owner or operator has obtained a groundwater management zone, and any corrective action taken to remediate the groundwater.

e) Operating permits must be issued for fixed terms not to exceed five years.

Section 845.240 Pre-Application Public Notification and Public Meeting

a) At least 30 days before the submission of a construction permit application, the owner or operator of the CCR surface impoundment must hold at least two public meetings to discuss the proposed construction, with at least one meeting to be held after 5:00 p.m. in the evening. Any public meeting held under this Section must be located at a venue that is accessible to persons with disabilities, and the owner or operator must provide reasonable accommodations upon request.

b) The owner or operator must prepare and circulate a notice explaining the proposed construction project and any related activities and the time and place of the public meeting. At least 30 days before the public meeting, the owner or operator of the CCR surface impoundment must:

1) Mail or hand-deliver the notice to the Agency and all residents within a one-mile radius from the facility boundary;

2) Post the notice to the owner's or operator's publicly accessible Internet site under Section 845.810;

3) Post the notice in conspicuous locations throughout villages, towns, or cities within 10 miles of the facility, or use appropriate broadcast media (such as radio or television);

4) Request that the Agency email the notice to the Agency's listserv for the facility; and

5) Include in the notice the owner's and operator's contact information, the internet address where the information in Section 845.240(e) will be posted, and the date on which the information will be posted to the site.

c) When a proposed construction project or any related activity is located in an area with a significant proportion of non-English speaking residents, the notification must be circulated, or broadcast, in both English and the appropriate non-English language, and the owner or operator must provide translation services during the public meetings required by Section 845.240(a), if requested by non-English speaking members of the public.

d) The owner or operator of the CCR surface impoundment must prepare documentation recording the public meeting and place the documentation in the facility's operating record as required by Section 845.800(d)(2).

e) At least 30 days before a public meeting, the owner or operator of the CCR surface impoundment must post on the owner's or operator's publicly accessible internet site all documentation relied upon in making a tentative construction permit application.

f) At the public meeting, the owner or operator of the CCR surface impoundment must:

1) Present its decision-making process for the construction permit application, including, when applicable, the corrective action alternatives and the closure alternatives considered. The presentation must include a comparison of projected groundwater impacts for each alternative considered and an objective comparison of the pros and cons of each alternative considered;

2) Include a question/answer portion of the meeting to allow the public to ask questions. There must be representatives from the owner or operator present who are qualified and knowledgeable enough to answer the questions posed by the public.

3) If there are questions posed by the public at the hearing that cannot be answered in person or if there are subsequent questions posed by the public following the meeting, the owner or operator of the facility must respond to those questions in writing within a reasonable timeframe and post the response on the facility's CCR website required by Section 845.810; and

4) Explain that the Agency is creating a listserv for the facility, compile a list of interested persons in attendance—and their respective email addresses—who would like to be added to the listserv, and transmit that list to the Agency with the permit application.

g) Within 14 days after the public meetings required by Section 845.240, the owner or operator must distribute a general summary of the issues raised by the public, as well as a response to those issues or comments raised by the public. If these comments resulted in a revision, change in a decision, or other considerations or determination, a summary of these revisions, changes and considerations must be included in the summary. The summary must be distributed to any attendee who requests a copy at the public meeting.

h) This Section does not apply to applications for minor modifications as described in Section 845.280(d).

Section 845.250 Tentative Determination and Draft Permit

Following the receipt of a complete application for a construction permit, operating permit, or joint construction and operating permit, the Agency must prepare a tentative determination.

a) The tentative determination must include at least the following:

1) A statement regarding whether the permit is to be issued or denied; and

2) If the determination is to issue the permit, a draft permit and a brief description of any conditions contained in the permit.

b) Upon tentative determination to issue or deny the permit:

1) If the determination is to issue the permit, the Agency must notify the applicant in writing of the content of the tentative determination and draft permit and of its intent to circulate public notice of issuance in accordance with Section 845.260;

2) If the determination is to deny the permit, the Agency must notify the applicant in writing of the tentative determination and of its intent to circulate public notice of denial, in accordance with Section 845.260. In the case of denial, notice to the applicant must include a statement of the reasons for denial, as required by Section 39(a) of the Act.

c) The documents supporting the Agency's tentative decision to issue or deny a permit must be made part of the Agency's record.

Section 845.260 Draft Permit Public Notice and Participation

a) The Agency must post a notification that it has received a permit application on the Agency's webpage and must email the notice to the Agency's listserv for the applicant's facility.

b) Public Notice of Draft Permit

1) Not earlier than 15 days following the Agency's notification to the applicant of its tentative decision under Section 845.250 to issue or deny the permit application, the Agency must circulate public notice of the completed application for the permit in a manner designed to inform interested and potentially interested persons of the construction, modification, operation or closure of a CCR surface impoundment and of the proposed determination to issue or deny the permit.

2) The contents of public notice of completed applications for permits must include at least the following:

A) Name, address, and telephone number of the Agency;

B) Name and address of the applicant;

C) Brief description of the applicant's activities or operations that result in the construction, operation, modification or closure of a CCR surface impoundment;

D) A statement of the tentative determination to issue or deny the permit;

E) A brief description of the procedures for the formulation of final determinations, including the procedures for submitting comments and the expiration date of the comment period;

F) Address and telephone number of Agency premises at which interested persons may obtain further information and request a copy of the permit application and related documents;

G) A translation of the public notice into the appropriate language or languages will be made if the Agency determines that a project is located within one mile of a significant population of non-English speaking residents;

H) A brief description of how members of the public can request a public hearing under Section 845.260(d); and

I) A brief description of how members of the public can request being added to the Agency's listserv for the facility.

3) Procedures for the circulation of public notice required under this Section must include at least the following concurrent actions:

A) Posting on the Agency's webpage and all the Agency's social media outlets;

B) Mailing the notice to the clerk of the nearest city, town or village requesting further posting in conspicuous locations throughout the city, town or village;

C) Requiring the applicant to post the notice near the entrance to the applicant's premises; and

D) Emailing the notice to the Agency's listserv for the facility.

c) Public Comment Period

1) The Agency must accept written comments from interested persons on the draft permit determination for 45 days following the circulation of the public notice under subsection (b).

2) All comments must be submitted to the Agency and to the applicant.

3) The Agency must keep all timely submitted comments and consider them in the formulation of its final determination with respect to the permit application.

4) The period for comment may be extended at the discretion of the Agency.

d) Public Hearing

1) The Agency must hold a public hearing on the issuance or denial of a draft permit whenever the Agency determines that there exists a significant degree of public interest in the proposed permit.

2) Within the 45-day public comment period, any person, including the applicant, may submit to the Agency a request for a public hearing, which must include the reasons why a hearing is warranted.

3) Hearings held under this Section must be held in the geographical area in which the CCR surface impoundment is located. When determining the hearing location, consideration must be given to facilitating attendance of interested or affected persons and organizations and to accessibility of hearing sites to public transportation.

e) Notice of Public Hearing

1) The Agency must issue notice of a public hearing not less than 30 days before the date of the hearing, under the procedures for the circulation of public notice in subsection (b)(3).

2) The contents of the public notice for the public hearing must include at least the following:

A) Name, address, and telephone number of the Agency;

B) Name and address of each applicant whose application will be considered at the hearing;

C) Brief description of the applicant's activities or operations that result in the construction, operation, modification or closure of a CCR surface impoundment;

D) Information regarding the time and location of the hearing;

E) The purpose of the hearing;

F) A concise statement of the issues to be considered at the hearing;

G) Address and telephone number of premises at which interested persons may obtain further information and request a copy of the draft permit and related documents; and

H) A statement that the hearing will be conducted in accordance with this Section.

I) A translation of the public notice into the appropriate language or languages will be made if the Agency determines that a project is located within one mile of a significant population of non-English speaking residents.

f) When the Agency receives written comments or holds a public hearing under this Section, the Agency must prepare a responsiveness summary that includes:

1) An identification of the public participation activity conducted;

2) Description of the matter on which the public was consulted;

3) An estimate of the number of persons present at the hearing;

4) A summary of all significant comments, criticisms, and suggestions, whether written or oral, submitted during the public comment period, at the hearing, or during the time the hearing record was open;

5) The Agency's response to all significant comments, criticisms, and suggestions; and

6) A statement of Agency action, including, when applicable, the issuance or denial of the permit.

Section 845.270 Final Permit Determination and Appeal

a) The Agency must not make a final permit determination until the public participation process in Section 845.260 has concluded.

b) After the consideration of any comments that may have been received, the Agency may either issue or deny the permit.

c) The Agency must provide a notice of the issuance or denial of the permit to the applicant, to any person who provides comments or an email address to the Agency during the public notice period or a public hearing, and to any person on the Agency's listserv for the facility. The Agency must post its final permit determination and, if a public hearing was held, the responsiveness summary, to the Agency's website. The notice must briefly indicate any significant changes that were made from the terms and conditions of the draft permit.

d) In the case of denial, the Agency must inform the applicant of the reasons for denial, as required by Section 39(a) of the Act.

e) Appeal

1) If the Agency refuses to grant, or grants with conditions, a permit under this Part, the applicant may petition the Board to appeal the Agency's final decision under Section 40 of the Act.

2) *If the Agency grants or denies a permit under this Part, a third party, other than the permit applicant or Agency, may appeal the Agency's decision as provided under federal law for CCR surface impoundment permits.* [415 ILCS 5/40(g)]

3) All appeals must be filed with the Board within 35 days after the final action is served on the applicant.

Section 845.280 Transfer, Modification and Renewal

a) No permit is transferable from one person to another except as approved by the Agency. Approval must be granted only if a new owner or operator seeking transfer of a permit can demonstrate the ability to comply with all applicable financial requirements of Subpart I.

b) Agency Initiated Modification. The Agency may modify a permit under the following conditions:

1) Discovery of a typographical or calculation error;

2) Discovery that a determination or condition was based upon false or misleading information;

3) An order of the Board issued in an action brought under Title VII, VIII, IX or X of the Act; or

4) Promulgation of new statutes or regulations affecting the permit.

c) The owner or operator of a CCR surface impoundment may initiate modification to its permit by application submittal to the Agency at any time after the permit is approved and before the permit expires.

d) The Agency may make minor modifications to a permit without following the public notice procedures of Section 845.260. Minor modifications may only:

1) Correct typographical errors;

2) Require more frequent monitoring or reporting by the permittee, including the installation of additional groundwater monitoring wells;

3) Allow for a change in ownership or operational control of a facility when the Agency determines that no other change in the permit is necessary, provided that a written agreement containing a specific date for transfer of permit responsibility, coverage, and liability between the current and new permittees has been submitted to the Agency;

4) Change the construction schedule, which does not impact the scheduled date of completion; or

5) Require electronic reporting requirements.

e) An application for renewal of a permit must be filed with the Agency at least 180 days before the expiration date of the existing permit unless the Agency grants a waiver of this requirement. The Agency may grant a waiver of the 180-day requirement only if:

1) The permittee submits a written request to the Agency at least 60 days before the expiration of the permit;

2) The permittee's written request includes the reasonably justifiable causes for not meeting the 180-day requirement; and

3) The permittee's written request includes a date by which the permittee will submit the renewal application.

f) Any Agency decision to deny a waiver request must be made within 21 days after receipt of the waiver request (see subsection (e)(1)).

g) The terms and conditions of an expiring permit remain effective and enforceable against the permittee until the Agency takes final action on the pending permit renewal application, only if the permittee has submitted a timely application under subsection (e) and the Agency, through no fault of the permittee, does not issue a new permit by the expiration date of the previous permit.

Section 845.290 Construction Quality Assurance Program

a) The following must be constructed according to a Construction Quality Assurance (CQA) program:

1) The construction of a new CCR surface impoundment, or the lateral expansion of an existing CCR surface impoundment;

2) The retrofit of an existing CCR surface impoundment;

3) Installation of a groundwater collection system and discharge system;

4) Installation of the groundwater monitoring system; and

5) Installation of the final cover system.

b) The CQA program must meet the following requirements:

1) The owner or operator of the CCR surface impoundment must designate a CQA officer who is a qualified professional engineer.

2) At the end of each week of construction, until construction is complete, a summary report must be prepared either by the CQA officer or under the supervision of the CQA officer. The report must include descriptions of the weather, locations where construction occurred during the previous week, materials used, results of testing, inspection reports, and procedures used to perform the inspections. The CQA officer must review and approve the report. The owner or operator of the CCR surface impoundment must place the weekly reports in the facility's operating record (see Section 845.800(d)(3)).

3) The CQA officer must certify the following, when applicable:

A) The bedding material contains no undesirable objects;

B) The final closure plan or corrective action plan approved by the construction permit has been followed;

C) The anchor trench and backfill are constructed to prevent damage to a geosynthetic membrane;

D) All tears, rips, punctures, and other damage are repaired;

E) All geosynthetic membrane seams are properly constructed and tested in accordance with the manufacturer's specifications;

F) Any groundwater collection system is constructed to intersect the water table;

G) Any groundwater collection system is properly constructed to slope toward extraction points, and the extraction equipment is properly designed and installed;

H) Appropriate operation and maintenance plans for the groundwater collection system and extraction and discharge equipment are provided;

I) Proper filter material consisting of uniform granular fill, to avoid clogging, is used in construction;

J) The filter material, as placed, possesses structural strength adequate to support the maximum loads imposed by the overlying materials and equipment used at the facility;

K) CCR stabilization; and

L) Site restoration, if any.

4) The CQA officer must supervise and be responsible for all inspections, testing and other activities required to be implemented as part of the CQA program under this Section.

5) The CQA officer must be present to provide supervision and assume responsibility for performing all inspections of the following activities, when applicable:

A) Compaction of the subgrade and foundation to design parameters;

B) Application of final cover, including installation of the geomembrane; and

C) Installation of the groundwater collection system and discharge system.

6) If the CQA officer is unable to be present as required by subsection (b)(5), the CQA officer must provide the following in writing:

A) The reasons for his or her absence;

B) A designation of a person who must exercise professional judgment in carrying out the duties of the CQA officer-in-absentia; and

C) A signed statement that the CQA officer assumes full responsibility for all inspections performed and reports prepared by the designated CQA officer-in-absentia during the absence of the CQA officer.

7) The CQA program must ensure, at a minimum, that construction materials and operations meet design specifications.

SUBPART C: LOCATION RESTRICTIONS

Section 845.300 Placement Above the Uppermost Aquifer

a) Existing and new CCR surface impoundments, and all lateral expansions of CCR surface impoundments, must be constructed with a base that is located at least 1.52 meters (five feet) above the upper limit of the uppermost aquifer, or must demonstrate that there will not be an intermittent, recurring, or sustained hydraulic connection between any portion of the base of the CCR surface impoundment and the uppermost aquifer due to normal fluctuations in groundwater elevations (including the seasonal high water table).

b) The owner or operator of the CCR surface impoundment must obtain a certification from a qualified professional engineer stating that the demonstration meets the requirements of subsection (a).

c) The owner or operator of an existing CCR surface impoundment must complete the demonstration required by subsection (a) and submit the completed demonstration, along with a qualified professional engineer's certification, to the Agency in the facility's initial operating permit application.

d) The owner or operator of a new CCR surface impoundment or a lateral expansion of a CCR surface impoundment must submit plans and specifications in a construction permit application that demonstrate the CCR surface impoundment will be constructed under subsection (a). Upon completion of construction, the owner or operator must obtain a certification from a qualified professional engineer that the CCR surface impoundment or lateral expansion was constructed in accordance with the requirements in subsection (a) and submit the certification to the Agency in the facility's initial operating permit application.

Section 845.310 Wetlands

a) Existing and new CCR surface impoundments, and all lateral expansions of CCR surface impoundments, must not be located in wetlands unless the owner or operator demonstrates the following:

   1) When applicable under section 404 of the Clean Water Act, Interagency Wetlands Policy Act of 1989 [20 ILCS 830] and Rivers, Lakes, and Streams Act [615 ILCS 5], or other applicable State wetlands laws, a clear and objective rebuttal of the presumption that an alternative to the CCR surface impoundment is reasonably available that does not involve wetlands.

   2) The construction and operation of the CCR surface impoundment will not cause or contribute to any of the following:

      A) A violation of any applicable State or federal water quality standard;

B) A violation of any applicable toxic effluent standard or prohibition under section 307 of the Clean Water Act;

C) Jeopardize the continued existence of endangered or threatened species or result in the destruction or adverse modification of a critical habitat, protected under the Endangered Species Act of 1973 (16 USC 1531 et seq.) and the Illinois Endangered Species Protection Act [520 ILCS 10]; and

D) A violation of any requirement under the Marine Protection, Research, and Sanctuaries Act of 1972 (16 USC 1431 and 33 USC 1401) for the protection of a marine sanctuary.

3) The CCR surface impoundment will not cause or contribute to significant degradation of wetlands by addressing all the following factors:

A) Erosion, stability, and migration potential of native wetland soils, muds and deposits used to support the CCR surface impoundment;

B) Erosion, stability, and migration potential of dredged and fill materials used to support the CCR surface impoundment;

C) The volume and chemical nature of the CCR;

D) Impacts on fish, wildlife, and other aquatic resources and their habitat from release of CCR;

E) The potential effects of catastrophic release of CCR to the wetland and the resulting impacts on the environment; and

F) Any additional factors, as necessary, to demonstrate that ecological resources in the wetland are sufficiently protected.

4) To the extent required under section 404 of the Clean Water Act or applicable State wetlands laws, steps have been taken to attempt to achieve no net loss of wetlands (as defined by acreage and function) by first avoiding impacts to wetlands to the maximum extent reasonable as required by subsections (a)(1) through (3), then minimizing unavoidable impacts to the maximum extent reasonable, and, finally, offsetting remaining unavoidable wetland impacts through all appropriate and reasonable compensatory mitigation actions (e.g., restoration of existing degraded wetlands or creation of man-made wetlands); and

5) Sufficient information is available to make a reasoned determination with respect to the demonstrations in subsections (a)(1) through (4).

b) The owner or operator of the CCR surface impoundment must obtain a certification from a qualified professional engineer stating that the demonstration meets the requirements of subsection (a).

c) The owner or operator of an existing CCR surface impoundment must complete the demonstration required by subsection (a) and submit the completed demonstration, along with the qualified professional engineer's certification, to the Agency with the facility's initial operating permit application.

d) The owner or operator of a new CCR surface impoundment or a lateral expansion of a CCR surface impoundment must submit plans and specifications in a construction permit application that demonstrate the CCR surface impoundment will be constructed under subsection (a). Upon completion of construction, the owner or operator must obtain a certification from a qualified professional engineer that the CCR surface impoundment or lateral expansion was constructed in accordance with the requirements in subsection (a) and submit the certification to the Agency in the facility's initial operating permit application.

Section 845.320 Fault Areas

a) Existing and new CCR surface impoundments, and all lateral expansions of CCR surface impoundments, must not be located within 60 meters (200 feet) of the outermost damage zone of a fault that has had displacement in Holocene time unless the owner or operator demonstrates that an alternative setback distance of less than 60 meters (200 feet) will prevent damage to the structural integrity of the CCR surface impoundment.

b) The owner or operator of the CCR surface impoundment must obtain a certification from a qualified professional engineer stating that the demonstration meets the requirements of subsection (a).

c) The owner or operator of an existing CCR surface impoundment must complete the demonstration required by subsection (a) and submit the completed demonstration, along with the qualified professional engineer's certification, to the Agency with the facility's initial operating permit application.

d) The owner or operator of a new CCR surface impoundment or a lateral expansion of a CCR surface impoundment must submit plans and specifications in a construction permit application that demonstrate the CCR surface impoundment will be constructed under subsection (a). Upon completion of construction, the owner or operator must obtain a certification from a qualified professional engineer that the CCR surface impoundment or lateral expansion was constructed in accordance with the requirements in subsection (a) and submit the certification to the Agency in the facility's initial operating permit application.

Section 845.330 Seismic Impact Zones

a) Existing and new CCR surface impoundments, and all lateral expansions of CCR surface impoundments, must not be located in seismic impact zones unless the owner or operator demonstrates that all structural components, including liners, leachate collection and removal systems, and surface water control systems, are designed to resist the maximum horizontal acceleration in lithified earth material for the site.

b) The owner or operator of the CCR surface impoundment must obtain a certification from a qualified professional engineer stating that the demonstration meets the requirements of subsection (a).

c) The owner or operator of an existing CCR surface impoundment must complete the demonstration required by subsection (a) and submit the completed demonstration, along with the qualified professional engineer's certification, to the Agency with the facility's initial operating permit application.

d) The owner or operator of a new CCR surface impoundment or a lateral expansion of a CCR surface impoundment must submit plans and specifications in a construction permit application that demonstrate the CCR surface impoundment will be constructed under subsection (a). Upon completion of construction, the owner or operator must obtain a certification from a qualified professional engineer that the CCR surface impoundment or lateral expansion was constructed in accordance with the requirements of subsection (a) and submit the certification to the Agency in the facility's initial operating permit application.

Section 845.340 Unstable Areas and Floodplains

a) An existing or new CCR surface impoundment, or any lateral expansion of a CCR surface impoundment, must not be located in an unstable area unless the owner or operator demonstrates that recognized and generally accepted engineering practices have been incorporated into the design of the CCR surface impoundment to ensure that the integrity of the structural components of the CCR surface impoundment will not be disrupted.

b) The owner or operator must consider all the following factors, at a minimum, when determining whether an area is unstable:

   1) On-site or local soil conditions, including liquefaction, that may result in significant differential settling;

   2) On-site or local geologic or geomorphologic features; and

   3) On-site or local human-made features or events (both surface and subsurface).

c) An existing or new CCR surface impoundment, or any lateral expansion of a CCR surface impoundment, must not be located in a floodplain unless the owner or operator demonstrates that recognized and generally accepted engineering practices have been incorporated into the design of the CCR surface impoundment to ensure that the CCR surface impoundment will not restrict the flow of the base flood, reduce the temporary water storage capacity of a floodplain, or result in washout of CCR, so as to pose a hazard to human life, wildlife, or land or water resources. For purposes of this subsection (c):

1) Base flood means a flood that has a 1 percent or greater chance of recurring in any year or a flood of a magnitude equaled or exceeded once in 100 years on average within the time of historical river level records.

2) Floodplain means the lowland and relatively flat areas adjoining inland and coastal waters, including flood-prone areas of offshore islands, which are inundated by the base flood.

3) Washout means the carrying away of CCR by waters of the base flood.

d) The owner or operator of the CCR surface impoundment must obtain a certification from a qualified professional engineer stating that the demonstration meets the requirements of subsections (a) and (c).

e) The owner or operator of an existing CCR surface impoundment must complete the demonstration required by subsections (a) and (c) of this Section and submit the completed demonstration, along with a qualified professional engineer's certification, to the Agency with the facility's initial operating permit application.

f) The owner or operator of a new CCR surface impoundment, or a lateral expansion of a CCR surface impoundment, must submit plans and specifications in a construction permit application that demonstrate the CCR surface impoundment will be constructed under subsections (a)and (c). Upon completion of construction, the owner or operator must obtain a certification from a qualified professional engineer that the CCR surface impoundment or lateral expansion was constructed in accordance with the requirements in subsections (a) and (c) and submit the certification to the Agency in the facility's initial operating permit application.

Section 845.350 Failure to Meet Location Standards

a) An owner or operator of an existing CCR surface impoundment who fails to demonstrate compliance with the requirements of this Subpart is subject to the requirements of Section 845.700.

b) An owner or operator of a new CCR surface impoundment, or any lateral expansion of a CCR surface impoundment, who fails to make the demonstration showing compliance with the requirements of this Subpart is prohibited from placing CCR in the CCR surface impoundment.

SUBPART D: DESIGN CRITERIA

Section 845.400 Liner Design Criteria for Existing CCR Surface Impoundments

a) An existing CCR surface impoundment is considered to be an existing lined surface impoundment if it has been constructed with either a composite liner that meets the requirements of subsection (b) or an alternative composite liner that meets the requirements of subsection (c).

b) Composite Liner

1) A composite liner must consist of two components: the upper component consisting of, at a minimum, a 30-mil geomembrane liner, and the lower component consisting of at least a two-foot layer of compacted soil with a hydraulic conductivity of no more than 1 x 10^{-7} centimeters per second (cm/sec). The geomembrane liner components consisting of high-density polyethylene (HDPE) must be at least 60 mil. The geomembrane liner or upper liner component must be installed in direct and uniform contact with the compacted soil or lower liner component.

2) The composite liner must be:

A) Constructed of materials that have appropriate chemical properties and sufficient strength and thickness to prevent failure due to pressure gradients (including static head and external hydrogeologic forces), physical contact with the CCR or leachate to which they are exposed, climatic conditions, the stress of installation, and the stress of daily operation;

B) Constructed of materials that provide appropriate shear resistance of the upper and lower component interface to prevent sliding of the upper component, including on slopes;

C) Placed upon a foundation or base capable of providing support to the liner and resistance to pressure gradients above and below the liner to prevent failure of the liner due to settlement, compression, or uplift; and

D) Installed to cover all surrounding earth likely to be in contact with the CCR or leachate.

c) Alternative Composite Liner

1) An alternative composite liner must consist of two components: the upper component consisting of, at a minimum, a 30-mil geomembrane liner, and a lower component, that is not a geomembrane, with a liquid flow rate no greater than the liquid flow rate of two feet of compacted soil with a hydraulic conductivity of no more than 1 x 10^{-7} cm/sec. The geomembrane liner components consisting of high-density polyethylene (HDPE) must be at least 60 mil. If the lower component of the alternative liner is compacted soil, the geomembrane liner must be installed in direct and uniform contact with the compacted soil.

2) The liquid flow rate through the lower component of the alternative composite liner must be no greater than the liquid flow rate through two feet of compacted soil with a hydraulic conductivity of 1 x 10^{-7} cm/sec. The hydraulic conductivity for the two feet of compacted soil used in the comparison must be no greater than 1 x 10^{-7} cm/sec. The hydraulic conductivity of any alternative to the two feet of compacted soil must be determined using recognized and generally accepted methods.

3) The liquid flow rate comparison must be made using the following equation, which is derived from Darcy's Law for gravity flow through porous media.

$$Q/A = q = k\,((h/t)+1)$$

Where:
Q = flow rate (cubic centimeters/second)
A = Surface area of the liner (squared centimeters)
q = flow rate per unit area (cubic centimeters/ second/squared centimeter)
k = hydraulic conductivity of the liner (centimeters /second)
h = hydraulic head above the liner (centimeters); and
t = thickness of the liner (centimeters)

4) The alternative composite liner must meet the requirements specified in subsection (b).

d) The hydraulic conductivity of the compacted soil must be determined using recognized and generally accepted methods.

e) The owner or operator of an existing CCR surface impoundment that has not completed an Agency approved closure before July 30, 2021 must submit an initial operating permit application under Section 845.230 that demonstrates whether the CCR surface impoundment was constructed with either of the following:

1) A composite liner that meets the requirements of subsection (b); or

2) An alternative composite liner that meets the requirements of subsection (c).

f) A CCR surface impoundment is considered to be an unlined CCR surface impoundment if either:

1) The owner or operator of the CCR surface impoundment determines that the CCR surface impoundment is not constructed with a liner that meets the requirements of subsection (b) or (c); or

2) The owner or operator of the CCR surface impoundment fails to document whether the CCR surface impoundment was constructed with a liner that meets the requirements of subsection (b) or (c).

g) All unlined CCR surface impoundments are subject to the requirements of Section 845.700.

h) The owner or operator of the CCR surface impoundment must obtain a certification from a qualified professional engineer attesting that the CCR surface impoundment meets the requirements of subsection (a) and submit the certification to the Agency in the facility's initial operating permit application.

Section 845.410 Liner Design Criteria for New CCR Surface Impoundments and Any Lateral Expansion of a CCR Surface Impoundment

a) New CCR surface impoundments and lateral expansions of existing and new CCR surface impoundments must be designed, constructed, operated, and maintained with either a composite liner or an alternative composite liner that meets the requirements of Section 845.400(b) or (c).

b) Any liner specified in this Section must be installed to cover all surrounding earth likely to be in contact with CCR. Dikes must not be constructed so as to damage the composite liner.

c) Before construction, the owner or operator must obtain certification from a qualified professional engineer that the design of the composite liner or, if applicable, the design of an alternative composite liner complies with the requirements of this Section and submit this certification to the Agency in the facility's construction permit application.

d) Upon completion of construction, the owner or operator must obtain a certification from a qualified professional engineer that the composite liner or, if applicable, the alternative composite liner has been constructed in accordance with the requirements of this Section and submit this certification to the Agency in the facility's initial operating permit application.

Section 845.420 Leachate Collection and Removal System

A new CCR surface impoundment must be designed, constructed, operated and maintained with a leachate collection and removal system. The leachate collection and removal system must be designed, constructed, operated, and maintained to collect and remove leachate from the leachate collection system of the CCR surface impoundment during its active life and post-closure care period.

a) The leachate collection and removal system must:

1) Be placed above the liner required by Section 845.400 or Section 845.410;

2) Have placed above it a filter layer that has a hydraulic conductivity of at least 1×10^{-5} cm/sec;

3) Have a bottom slope of three percent or more towards the collection pipes;

4) Be constructed of:

A) Granular drainage materials with a hydraulic conductivity of 1×10^{-1} cm/sec or more and a thickness of 24 inches or more above the crown of the collection pipe; or

B) Synthetic drainage materials with a transmissivity of 6×10^{-4} m^2/sec or more;

5) Be constructed of materials that are chemically resistant to CCR and any non-CCR waste managed in the CCR surface impoundment and the leachate expected to be generated, and of sufficient strength and thickness to prevent collapse under the pressures exerted by overlying waste and any waste cover materials and equipment used at the CCR surface impoundment;

6) Be designed, constructed and operated with collection pipes at the base of the granular material to prevent clogging with fines during the active life and post-closure care period;

7) Have collection pipes

A) Designed such that leachate is collected at a sump and is pumped or flows out of the CCR surface impoundment;

B) With slopes that allow flow from all points within the CCR surface impoundment to the sump or drain outlet; and

C) Large enough to conduct periodic cleaning;

8) Have a protective layer or other means of deflecting the force of CCR pumped into the CCR surface impoundment;

9) Be designed and operated to minimize clogging during the active life and post-closure care period; and

10) At a minimum, the leachate collection and removal system must be operated to remove free liquids from the CCR surface impoundment at the time of closure and during post closure care.

b) The owner or operator must obtain certification from a qualified professional engineer that the design of the leachate collection system complies with the requirements of this Section and submit this certification to the Agency in the facility's construction permit application.

c) Upon completion, the owner or operator must obtain a certification from a qualified professional engineer that the leachate collection system has been constructed in accordance with the requirements of this Section and submit this certification to the Agency in the facility's initial operating permit application.

Section 845.430 Slope Maintenance

The slopes and pertinent surrounding areas of the CCR surface impoundment must be designed, constructed, operated, and maintained with one of the forms of slope protection specified in subsection (a) that meets all the performance standards of subsection (b).

a) Slope protection must consist of one of the following:

1) A vegetative cover consisting of grassy vegetation;

2) An engineered cover consisting of a single form or combination of forms of engineered slope protection measures; or

3) A combination of the forms of cover specified in subsection (a)(1) or (a)(2).

b) Any form of cover for slope protection must meet the following performance standards:

1) The cover must be installed and maintained on the slopes and pertinent surrounding areas of the CCR surface impoundment;

2) The cover must provide protection against surface erosion, wave action, and adverse effects of rapid drawdown;

3) The cover must be maintained to allow for the observation of, and access to, the slopes and pertinent surrounding areas during routine and emergency events;

4) Woody vegetation must be removed from the slopes or pertinent surrounding areas. Any removal of woody vegetation with a diameter greater than ½ inch must be directed by a person familiar with the design and operation of the CCR surface impoundment and in consideration of the complexities of removal of a tree or shrubbery, who must ensure the removal does not create a risk of destabilizing the CCR surface impoundment or otherwise adversely affect the stability and safety of the CCR surface impoundment or personnel undertaking the removal; and

5) The height of vegetation must not exceed 12 inches.

Section 845.440 Hazard Potential Classification Assessment

a) Hazard Potential Classification Assessments

1) The owner or operator of the CCR surface impoundment must conduct an initial and annual hazard potential classification assessment of the CCR surface impoundment. The owner or operator must document the hazard potential classification of each CCR surface impoundment as either a Class 1 or Class 2 CCR surface impoundment. The owner or operator must also document the basis for each hazard potential classification.

2) The owner or operator of the CCR surface impoundment must obtain a certification from a qualified professional engineer stating that the initial hazard potential classification and each annual classification was conducted in accordance with the requirements of this Section.

3) Timeframe for Submission of the Hazard Potential Classification Assessments and Certifications

A) The owner or operator of a new CCR surface impoundment must submit the initial hazard potential classification assessment certification with the initial operating permit application before the initial receipt of CCR in the surface impoundment.

B) The owner or operator of an existing CCR surface impoundment must submit the initial hazard potential classification assessment certification with its first annual inspection report required by Section 845.540(b).

C) The owner or operator of a CCR surface impoundment must submit the annual hazard potential classification assessment certification each year with the annual inspection required by Section 845.540(b).

D) The owner or operator of a CCR surface impoundment must place each hazard potential classification assessment in the facility's operating record (see Section 845.800(d)(4)).

b) The requirements of this Section apply to all CCR surface impoundments, except for those CCR surface impoundments that are incised CCR surface impoundments. If an incised CCR surface impoundment is subsequently modified (e.g., a dike is constructed) such that the CCR surface impoundment no longer meets the definition of an incised CCR surface impoundment, the CCR surface impoundment is subject to the requirements of this Section.

Section 845.450 Structural Stability Assessment

a) The owner or operator of a CCR surface impoundment must conduct initial and annual structural stability assessments and document whether the design, construction, operation, and maintenance of the CCR surface impoundment is consistent with recognized and generally accepted engineering practices for the maximum volume of CCR and CCR wastewater that can be impounded in the CCR surface impoundment. The assessment must, at a minimum, document whether the CCR surface impoundment has been designed, constructed, operated, and maintained with:

1) Stable foundations and abutments;

2) Adequate slope protection to protect against surface erosion, wave action, and adverse effects of sudden drawdown;

3) Dikes mechanically compacted to a density sufficient to withstand the range of loading conditions in the CCR surface impoundment;

4) Slope protection consistent with Section 845.430;

5) A single spillway or a combination of spillways configured as specified in subsection (a)(5)(A). The combined capacity of all spillways must be designed, constructed, operated, and maintained to adequately manage

flow during and following the peak discharge from the event specified in subsection (a)(5)(B).

A) All spillways must be either:

i) Of non-erodible construction and designed to carry sustained flows; or

ii) Earth- or grass-lined and designed to carry short-term, infrequent flows at non-erosive velocities where sustained flows are not expected.

B) The combined capacity of all spillways must adequately manage flow during and following the peak discharge from a:

i) Probable maximum flood for a Class 1 CCR surface impoundment; or

ii) 1000-year flood for a Class 2 CCR surface impoundment.

6) Hydraulic structures underlying the base of the CCR surface impoundment or passing through the dike of the CCR surface impoundment that maintain structural integrity and are free of significant deterioration, deformation, distortion, bedding deficiencies, sedimentation, and debris that may negatively affect the CCR surface impoundment; and

7) For CCR surface impoundments with downstream slopes that can be inundated by the pool of an adjacent water body, such as a river, stream or lake, downstream slopes that maintain structural stability during low pool of the adjacent water body or sudden drawdown of the adjacent water body.

b) The annual assessment described in this Section must identify any structural stability deficiencies associated with the CCR surface impoundment in addition to recommending corrective measures. If a deficiency or a release is identified during the periodic assessment, the owner or operator of the surface impoundment must submit to the Agency a construction permit application including documentation detailing proposed corrective measures and must obtain any necessary permits from the Agency as soon as feasible.

c) The owner or operator of the CCR surface impoundment must obtain a certification from a qualified professional engineer stating that the initial structural stability assessments and each annual assessment thereafter was conducted in accordance with the requirements.

d) Timeframe for Submission of Structural Stability Assessment

1) The owner or operator of a new CCR surface impoundment must submit the initial structural stability assessment certification with the initial operating permit application before the initial receipt of CCR in the surface impoundment.

2) The owner or operator of an existing CCR surface impoundment must submit the initial structural stability assessment certification with its first annual inspection report required by Section 845.540(b).

3) The owner or operator of a CCR surface impoundment must submit the annual structural stability assessment certification each year with the annual inspection required by Section 845.540(b).

4) The owner or operator of a CCR surface impoundment must place each structural stability assessment in the facility's operating record (see Section 845.800(d)(5)).

e) The requirements of this Section apply to all CCR surface impoundments, except for those CCR surface impoundments that are incised CCR surface impoundments. If an incised CCR surface impoundment is subsequently modified (e.g., a dike is constructed) such that the CCR surface impoundment no longer meets the definition of an incised CCR surface impoundment, the CCR surface impoundment is subject to the requirements of this Section.

Section 845.460 Safety Factor Assessment

a) The owner or operator of a CCR surface impoundment must conduct an initial and annual safety factor assessment for each CCR surface impoundment and document whether the calculated factors of safety for each CCR surface impoundment achieve the minimum safety factors specified in this Section for the critical cross-section of the embankment. The critical cross-section is the cross section anticipated to be the most susceptible of all cross-sections to structural failure based on appropriate engineering considerations, including loading conditions. The safety factor assessments must be supported by appropriate engineering calculations.

1) For new CCR surface impoundments, the calculated static factor of safety under the end-of-construction loading condition must equal or exceed 1.30. The assessment of this loading condition is only required for the initial safety factor assessment and is not required for subsequent assessments.

2) The calculated static factor of safety under the long-term, maximum storage pool loading condition must equal or exceed 1.50.

3) The calculated static factor of safety under the maximum surcharge pool loading condition must equal or exceed 1.40.

4) The calculated seismic factor of safety must equal or exceed 1.00.

5) For dikes constructed of soils that have susceptibility to liquefaction, the calculated liquefaction factor of safety must equal or exceed 1.20.

b) The owner or operator of the CCR surface impoundment must obtain a certification from a qualified professional engineer stating that the initial safety factor assessment and each annual assessment thereafter was conducted in accordance with the requirements of this Section.

c) Timeframe for Submission of the Safety Factor Assessment

1) The owner or operator of a new CCR surface impoundment must submit the initial safety factor assessment certification with the initial operating permit application before the initial receipt of CCR in the surface impoundment.

2) The owner or operator of an existing CCR surface impoundment must submit the initial safety factor assessment certification with its first annual inspection report required by Section 845.540(b).

3) The owner or operator of a CCR surface impoundment must submit the annual safety factor assessment certification each year with the annual inspection required by Section 845.540(b).

4) The owner or operator of a new CCR surface impoundment must place each safety factor assessment in the facility's operating record as required by Section 845.800(d)(6).

d) Failure to Document Minimum Safety Factors

1) For new CCR surface impoundments, until the date an owner or operator of a CCR surface impoundment documents that the calculated factors of safety achieve the minimum safety factors specified in this Section, the owner or operator is prohibited from placing CCR in the CCR surface impoundment.

2) An owner or operator of the CCR surface impoundment who either fails to complete a timely safety factor assessment or fails to demonstrate minimum safety factors as required by this Section is subject to the requirements of Section 845.700.

e) The requirements of this Section apply to all CCR surface impoundments, except for those CCR surface impoundments that are incised CCR surface impoundments. If an incised CCR surface impoundment is subsequently modified (e.g., a dike is constructed) such that the CCR surface impoundment no longer meets the definition of an incised CCR surface impoundment, the CCR surface impoundment is subject to the requirements of this Section.

SUBPART E: OPERATING CRITERIA

Section 845.500 Air Criteria

a) The owner or operator of a CCR surface impoundment, or any lateral expansion of a CCR surface impoundment, must adopt measures that will effectively minimize CCR from becoming airborne at the facility, including CCR fugitive dust originating from CCR surface impoundments, roads, and other CCR management and material handling activities.

b) CCR Fugitive Dust Control Plan. The owner or operator of the CCR surface impoundment must prepare and operate in accordance with a CCR fugitive dust control plan as specified in this subsection (b). This requirement applies in addition to, not in place of, any applicable standards under the Occupational Safety and Health Act (29 USC 15), including 29 CFR 1910.1018, 29 CFR 1910.1024, 29 CFR 1910.1025, 29 CFR 1910.1027, and 1910.1053, or any other State or federal law.

1) The CCR fugitive dust control plan must identify and describe the CCR fugitive dust control measures the owner or operator will use to minimize CCR from becoming airborne at the facility. The owner or operator must select, and include in the CCR fugitive dust control plan, the CCR fugitive dust control measures that are most appropriate for site conditions, along with an explanation of how the measures selected are applicable and appropriate for site conditions. Examples of control measures that may be appropriate include: locating CCR inside an enclosure or partial enclosure; operating a water spray or fogging system; reducing fall distances at material drop points; using wind barriers, compaction, or vegetative covers; establishing and enforcing reduced vehicle speed limits; paving and sweeping roads; covering trucks transporting CCR; reducing or halting operations during high wind events; or applying a daily cover.

2) The CCR fugitive dust control plan must include procedures to log every complaint from members of the public received by the owner or operator involving CCR fugitive dust events at the facility. The owner or operator must:

A) Include for each logged complaint the date of the complaint, the date of the incident, the name and contact information of the complainant, if given, and all actions taken to assess and resolve the complaint; and

B) Submit quarterly reports to the Agency no later than 14 days from the end of the quarter of all complaints received in that quarter, including the information required by subsection (b)(2)(A).

3) The CCR fugitive dust control plan must include a description of the procedures the owner or operator will follow to periodically assess the effectiveness of the control plan.

4) The owner or operator of a CCR surface impoundment must prepare an initial CCR fugitive dust control plan for the facility by October 31, 2021, or by initial receipt of CCR in any CCR surface impoundment at the facility if the owner or operator becomes subject to this Part after October 31, 2021.

5) Amendment of the Plan. The owner or operator of a CCR surface impoundment subject to the requirements may amend the written CCR fugitive dust control plan at any time provided the revised plan is submitted to the Agency. The owner or operator must amend the written plan whenever there is a change in conditions that would substantially affect the written plan in effect, such as the construction and operation of a new CCR surface impoundment.

6) The owner or operator must place the initial and any amendments to the fugitive dust control plan in the facility's operating record as required by Section 845.800(d)(7). The most recent fugitive dust control plan must be placed in the facility's operating record and available on the owner's or operator's CCR website before submitting a permit application under this Part.

7) The owner or operator must obtain a certification from a qualified professional engineer that the initial CCR fugitive dust control plan, or any subsequent amendment of it, meets the requirements of this Section.

c) Annual CCR Fugitive Dust Control Report. The owner or operator of a CCR surface impoundment must prepare an annual CCR fugitive dust control report that includes a description of the actions taken by the owner or operator to control CCR fugitive dust and the four quarterly fugitive dust complaint reports submitted under subsection (b)(2)(B). The annual CCR fugitive dust control report must be submitted as a part of the annual consolidated report required by Section 845.550.

Section 845.510 Hydrologic and Hydraulic Capacity Requirements for CCR Surface Impoundments

a) The owner or operator of an existing or new CCR surface impoundment or any lateral expansion of a CCR surface impoundment must design, construct, operate, and maintain an inflow design flood control system as specified in subsections (a)(1) and (2).

1) The inflow design flood control system must adequately manage flow into the CCR surface impoundment during and following the peak discharge of the inflow design flood specified in subsection (a)(3).

2) The inflow design flood control system must adequately manage flow from the CCR surface impoundment to collect and control the peak discharge resulting from the inflow design flood specified in subsection (a)(3).

3) The inflow design flood, at a minimum, is:

A) For a Class 1 CCR surface impoundment, as determined under Section 845.440(a), the probable maximum flood;

B) For a Class 2 CCR surface impoundment, as determined under Section 845.440(a), the 1000-year flood; or

C) For an incised CCR surface impoundment, the 25-year flood.

b) Discharge from the CCR surface impoundment must be handled in accordance with the surface water requirements in Section 845.110(b)(3) and 35 Ill. Adm. Code Subtitle C.

c) Inflow Design Flood Control System Plan

1) Content of the Plan. The owner or operator must prepare initial and annual inflow design flood control system plans for the CCR surface impoundment. These plans must document how the inflow design flood control system has been designed and constructed to meet the requirements of this Section. Each plan must be supported by appropriate engineering calculations.

2) Amendment of the Plan. The owner or operator of the CCR surface impoundment may amend the written inflow design flood control system plan at any time. The owner or operator must amend the written inflow design flood control system plan whenever there is a change in conditions that would substantially affect the written plan in effect.

3) The owner or operator must obtain a certification from a qualified professional engineer stating that the initial and periodic inflow design flood control system plans meet the requirements of this Section.

4) Timeframe for Plan Submission

A) The owner or operator of a new CCR surface impoundment must submit to the Agency the initial inflow design flood control system plan certification with the initial operating permit application before the initial receipt of CCR in the surface impoundment.

B) The owner or operator of an existing CCR surface impoundment must submit the initial inflow design flood control system plan certification with its first annual inspection report required by Section 845.540(b).

C) The owner or operator of a CCR surface impoundment must submit the annual inflow design flood control system plan certification each year with the annual inspection required by Section 845.540(b).

D) The owner or operator of a new CCR surface impoundment must place each inflow design flood control system plan in the facility's operating record (see Section 845.800(d)(8)).

Section 845.520 Emergency Action Plan

a) The owner or operator of a CCR surface impoundment must prepare and maintain a written Emergency Action Plan (EAP). The owner or operator must place the EAP and any amendment of the EAP in the facility's operating record (see Section 845.800(d)(9)).

b) At a minimum, the EAP must:

1) Define the events or circumstances involving the CCR surface impoundment that represent a safety emergency, along with a description of the procedures that will be followed to detect a safety emergency in a timely manner;

2) Define responsible persons, their respective responsibilities, and notification procedures for a safety emergency involving the CCR surface impoundment;

3) Provide contact information of emergency responders;

4) Include a map that delineates the downstream area that would be affected if a CCR surface impoundment fails and a physical description of the CCR surface impoundment; and

5) Include provisions for an annual face-to-face meeting or exercise between representatives of the owner or operator of the CCR surface impoundment and the local emergency responders.

c) The owner or operator of a CCR surface impoundment must prepare an initial Emergency Action Plan for the facility by October 31, 2021, or by initial receipt of CCR in any CCR surface impoundment at the facility if the owner or operator becomes subject to this Part after October 31, 2021.

d) Amendment of the Plan

1) The owner or operator of a CCR surface impoundment may amend the written EAP at any time.

2) The owner or operator must amend the written EAP whenever there is a change in conditions that would substantially affect the EAP in effect.

3) The written EAP must be evaluated, at a minimum, every five years to ensure the information required in this Section is accurate.

e) The owner or operator of the CCR surface impoundment must obtain a certification from a qualified professional engineer stating that the written EAP, and any subsequent amendment of the EAP, meets the requirements of this Section.

f) Activation of the EAP. The EAP must be implemented once events or circumstances involving the CCR surface impoundment that represent a safety emergency are detected, including conditions identified during any structural stability assessments, annual inspections, and inspections by a qualified person. The owner or operator of the CCR surface impoundment must submit records documenting all activations of the EAP to the Agency and place the documentation in the facility's operating record as required by Section 845.800(d)(10).

g) The owner or operator of a CCR surface impoundment must document the annual face-to-face meeting or exercise between representatives of the owner or operator of the CCR surface impoundment and the local emergency responders as required by subsection (b)(5). The owner or operator of the CCR surface impoundment must place this documentation in the facility's operating record as required by Section 845.800(d)(11).

Section 845.530 Safety and Health Plan

a) The owner or operator of the CCR surface impoundment must develop a Safety and Health Plan and ensure that employees, contract workers, and third-party contractors are informed regarding the Safety and Health Plan. The owner or operator must conduct ongoing worker hazard analyses and ensure employees, contract workers, and third-party contractors are aware of those analyses. The plan must be updated as needed based on the worker hazard analyses, but at least annually. The plan, and all amendments to the plan, must be placed in the facility's operating record as required by Section 845.800(d)(12), and on the owner's or operator's publicly accessible internet site.

b) For worker exposure safety, in addition to all other applicable local, State and federal requirements, the owner or operator of the CCR surface impoundment, for all chemical constituents identified in the CCR under Sections 845.230(a)(15) and 845.230(d)(2)(C), must:

1) Consider the recommendations in the most recent "NIOSH Pocket Guide to Chemical Hazards", Department of Human Health and Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health (available at cdc.gov/niosh/npg/default.html);

2) Implement the Occupational Safety and Health Administration regulations in Chapter 17 of Title 29 of the Code of Federal Regulations for all hazards not otherwise classified as defined in 29 CFR 1910.1200(c); and

3) Provide safety data sheets (Globally Harmonized System of Classification and Labeling of Chemicals adopted by OSHA) or create a facility-specific safety data sheet under 29 CFR 1910.1200(g).

c) The Safety and Health Plan must include a personnel training program that meets the following minimum requirements:

1) Employees, contract workers, and third-party contractors must successfully complete a training program that informs them of the hazards at the facility to ensure compliance with the requirements of this Part. The facility must maintain an outline of the training program used (or to be used) at the facility and a brief description of training program updates.

2) At a minimum, the training program must be designed to ensure that employees, contract workers, and third-party contractors understand and are able to respond effectively to the following:

A) Procedures for using, inspecting, repairing, and replacing facility emergency and monitoring equipment;

B) Communications or alarm systems;

C) Response to fires or explosions;

D) Response to a spill or release of CCR;

E) The training under the Occupational Safety and Health Standards in 29 CFR 1910.120, 29 CFR 1926.65, and the OSHA 10-hour or 30-hour construction safety training;

F) Information about chemical hazards and hazardous materials identified in subsection (b); and

G) The use of engineering controls, administrative controls, and personal protective equipment.

d) Employees, contract workers, and third-party contractors must successfully complete the program required in subsection (c) before undertaking any activity to construct, operate or close a CCR surface impoundment.

e) Employees, contract workers, and third-party contractors must take part in an annual review of the initial training required in subsection (c).

f) The owner or operator of the CCR surface impoundment must perform, at a minimum, the following hazard communication activities:

1) Post signs at the facility identifying the hazards of CCR, including dust inhalation when handling CCR;

2) Post signs at the facility identifying unstable CCR areas that may make operation of heavy equipment hazardous; and

3) Post signs at the facility where the CCR surface impoundment is located identifying safety measures and necessary precautions, including the proper use of personal protective equipment.

Section 845.540 Inspection Requirements for CCR Surface Impoundments

a) Inspections by a Qualified Person.

1) All CCR surface impoundments and any lateral expansion of a CCR surface impoundment must be examined by a qualified person as follows:

A) At intervals not exceeding seven days and after each 25-year, 24-hour storm, inspect for the following:

i) Any appearances of actual or potential structural weakness and other conditions that are disrupting, or have the potential to disrupt, the operation or safety of the CCR surface impoundment;

ii) Deterioration, malfunctions or improper operation of overtopping control systems, where present;

iii) Sudden drops in the level of the CCR surface impoundment's contents;

iv) Erosion that creates rills, gullies, or crevices six inches or deeper, other signs of deterioration including failed or eroded vegetation in excess of 100 square feet, or cracks in dikes or other containment devices; and

v) Any visible releases;

B) At intervals not exceeding seven days, inspect the discharge of all outlets of hydraulic structures that pass underneath the base of the CCR surface impoundment or through the dike, of the CCR surface impoundment, for abnormal discoloration, flow or discharge of debris or sediment; and

C) At intervals not exceeding 30 days, monitor all CCR surface impoundment instrumentation.

2) The owner or operator must prepare a report for each inspection that includes the date of the inspection, condition of the CCR surface impoundment, any repairs made to the CCR surface impoundment, and the date of the repair. The results of the inspection by a qualified person must be recorded in the facility's operating record as required by Section 845.800(d)(13).

3) The owner or operator of a CCR surface impoundment must initiate the inspections required by subsection (a) by April 30, 2021, or by initial receipt of CCR in a CCR surface impoundment if the owner or operator becomes subject to this Part after April 30, 2021. The inspections required by subsection (a) must continue until the completion of closure by removal or the completion of post-closure care.

4) If a 25-year, 24-hour storm is identified more than 48 hours before the next scheduled weekly inspection, an additional inspection must be conducted within 24 hours after the end of the identified storm event, before the scheduled seven-day inspection.

b) Annual Inspections By a Qualified Professional Engineer.

1) The CCR surface impoundment must be inspected on an annual basis by a qualified professional engineer to ensure that the design, construction,

operation, and maintenance of the CCR surface impoundment is consistent with recognized and generally accepted engineering standards. The inspection must, at a minimum, include:

A) A review of available information regarding the status and condition of the CCR surface impoundment, including files available in the operating record (e.g., CCR surface impoundment design and construction information required by Sections 845.220(a)(1) and 845.230(d)(2)(A), previous structural stability assessments required under Section 845.450, the results of inspections by a qualified person, and results of previous annual inspections);

B) A visual inspection of the CCR surface impoundment to identify signs of distress or malfunction of the CCR surface impoundment and appurtenant structures;

C) A visual inspection of any hydraulic structures underlying the base of the CCR surface impoundment or passing through the dike of the CCR surface impoundment for structural integrity and continued safe and reliable operation;

D) The annual hazard potential classification certification, if applicable (see Section 845.440);

E) The annual structural stability assessment certification, if applicable (see Section 845.450);

F) The annual safety factor assessment certification, if applicable (see Section 845.460); and

G) The inflow design flood control system plan certification (see Section 845.510(c)).

2) Inspection Report. The qualified professional engineer must prepare a report following each inspection that addresses the following:

A) Any changes in geometry of the impounding structure since the previous annual inspection;

B) The location and type of existing instrumentation and the maximum recorded readings of each instrument since the previous annual inspection;

C) The approximate minimum, maximum, and present depth and elevation of the impounded water and CCR since the previous annual inspection;

D) The storage capacity of the impounding structure at the time of the inspection;

E) The approximate volume of the impounded water and CCR at the time of the inspection;

F) Any appearances of an actual or potential structural weakness of the CCR surface impoundment, in addition to any existing conditions that are disrupting or have the potential to disrupt the operation and safety of the CCR surface impoundment and appurtenant structures; and

G) Any other changes that may have affected the stability or operation of the impounding structure since the previous annual inspection.

3) By January 31 of each year, the inspection report must be completed and included with the annual consolidated report required by Section 845.550.

4) Frequency of Inspections. The owner or operator of the CCR surface impoundment must conduct the inspection required by subsections (b)(1) and (2) on an annual basis. The deadline for conducting a subsequent inspection is based on the date of conducting the previous inspection.

5) If a deficiency or release is identified during an inspection, the owner or operator must submit to the Agency documentation detailing proposed corrective measures and obtain any necessary permits from the Agency.

Section 845.550 Annual Consolidated Report

a) By January 31 of each year, the owner or operator of the CCR surface impoundment must prepare an annual consolidated report for the preceding calendar year that includes the following:

1) Annual CCR fugitive dust control report (see Section 845.500(c));

2) Annual inspection report (see Section 845.540(b)), including:

A) Annual hazard potential classification certification, if applicable (see Section 845.440);

B) Annual structural stability assessment certification, if applicable (see Section 845.450);

C) Annual safety factor assessment certification, if applicable (see Section 845.460); and

D) Inflow design flood control system plan certification (see Section 845.510(c)).

3) Annual Groundwater Monitoring and Corrective Action Report (see Section 845.610(e)).

b) The owner or operator of the CCR surface impoundment must submit the annual consolidated report to the Agency in addition to placing the annual consolidated report in the facility's operating record as required by Section 845.800(d)(14).

SUBPART F: GROUNDWATER MONITORING AND CORRECTIVE ACTION

Section 845.600 Groundwater Protection Standards

a) For existing CCR surface impoundments and for inactive CCR surface impoundments:

1) The groundwater protection standards at the waste boundary must be:

A) Antimony: 0.006 mg/L

B) Arsenic: 0.010 mg/L

C) Barium: 2.0 mg/L

D) Beryllium: 0.004 mg/L

E) Boron: 2 mg/L

F) Cadmium: 0.005 mg/L

G) Chloride: 200 mg/L

H) Chromium: 0.1 mg/L

I) Cobalt: 0.006 mg/L

J) Fluoride: 4.0 mg/L

K) Lead: 0.0075 mg/L

L) Lithium: 0.04 mg/L

M) Mercury: 0.002 mg/L

N) Molybdenum: 0.1 mg/L

O) pH: 6.5-9.0 units

P) Selenium: 0.05 mg/L

Q) Sulfate: 400 mg/L

R) Thallium: 0.002 mg/L

S) Total Dissolved Solids: 1200 mg/L

T) Radium 226 and 228 combined: 5 pCi/L

2) For constituents with a background concentration higher than the levels identified in subsection (a)(1), the background concentration must be the groundwater protection standard.

b) For new CCR surface impoundments, the groundwater protection standards at the waste boundary must be background for the constituents listed in subsection (a)(1), calcium, and turbidity.

c) The owner or operator of a CCR surface impoundment may not obtain alternative groundwater quality standards in 35 Ill. Adm. Code 620.450(a)(4) for the constituents in subsections (a) and (b) before the end of post-closure care under Section 845.780, when closing with a final cover system, or before the end of groundwater monitoring under Section 845.740(b), when closing by removal.

Section 845.610 General Requirements

a) All CCR surface impoundments and lateral expansions of CCR surface impoundments are subject to the groundwater monitoring and corrective action requirements of this Subpart.

b) Required Submissions and Agency Approvals for Groundwater Monitoring

1) Existing CCR Surface Impoundments. The owner or operator of an existing CCR surface impoundment must submit the following to the Agency in an initial operating permit application:

A) A hydrogeologic site characterization meeting the requirements of Section 845.620;

B) Design and construction plans of a groundwater monitoring system meeting the requirements of Section 845.630;

C) A groundwater sampling and analysis program that includes selection of the statistical procedures to be used for evaluating groundwater monitoring data as required by Section 845.640; and

D) A monitoring program that includes a minimum of eight independent samples for each background and downgradient well as required by Section 845.650(b).

2) New CCR Surface Impoundments. The owner or operator of a new CCR surface impoundment and all lateral expansions of a CCR surface impoundment must submit the information required in subsections (b)(1)(A) through (C) in a construction permit application, and the information required in subsection (b)(1)(D) in an operating permit application.

3) All owners and operators of CCR surface impoundments must:

A) Conduct groundwater monitoring under a monitoring program approved by the Agency under this Subpart;

B) Evaluate the groundwater monitoring data for statistically significant levels over background levels for the constituents listed in Section 845.600 after each sampling event;

C) Determine compliance with the groundwater protection standards in Section 845.600 after each sampling event; and

D) Submit all groundwater monitoring data to the Agency and any analysis performed under subsections (b)(3)(B) and (b)(3)(C) within 60 days after completion of sampling, and place the groundwater monitoring data in the facility's operating record as required by Section 845.800(d)(15).

c) Once the groundwater monitoring system and the groundwater monitoring program have been established at the CCR surface impoundment as required by this Subpart, the owner or operator must conduct groundwater monitoring and, if necessary, corrective action throughout the active life and post-closure care period of the CCR surface impoundment or the time period specified in Section 845.740(b) when closure is by removal.

d) If a CCR surface impoundment has a release, the owner or operator must immediately take all necessary measures to control all sources of the release to reduce or eliminate, to the maximum extent feasible, further releases of contaminants into the environment. The owner or operator of the CCR surface impoundment must comply with all applicable requirements of Sections 845.660, 845.670, and 845.680.

e) Annual Groundwater Monitoring and Corrective Action Report

1) The owner or operator of the CCR surface impoundment must prepare and submit to the Agency an annual groundwater monitoring and corrective action report as a part of the annual consolidated report required by Section 845.550.

2) For the preceding calendar year, the annual report must document the status of the groundwater monitoring and corrective action plan for the CCR surface impoundment, summarize key actions completed, including the status of permit applications and Agency approvals, describe any problems encountered, discuss actions to resolve the problems, and project key activities for the upcoming year.

3) At a minimum, the annual groundwater monitoring and corrective action report must contain the following information, to the extent available:

A) A map, aerial image, or diagram showing the CCR surface impoundment, all background (or upgradient) and downgradient monitoring wells, including the well identification numbers, that are part of the groundwater monitoring program for the CCR surface impoundment, and a visual delineation of any exceedances of the groundwater protection standards;

B) Identification of any monitoring wells that were installed or decommissioned during the preceding year, along with a narrative description of why those actions were taken;

C) A potentiometric surface map for each groundwater elevation sampling event required by Section 845.650(b)(2);

D) In addition to all the monitoring data obtained under this Subpart, a summary including the number of groundwater samples that were collected for analysis for each background and downgradient well, and the dates the samples were collected;

E) A narrative discussion of any statistically significant increases over background levels for the constituents listed in Section 845.600; and

F) Other information required to be included in the annual report as specified in this Subpart.

4) A section at the beginning of the annual report must provide an overview of the current status of groundwater monitoring program and corrective action plan for the CCR surface impoundment. At a minimum, the summary must:

A) Specify whether groundwater monitoring data shows a statistically significant increase over background concentrations for one or more constituents listed in Section 845.600;

B) Identify those constituents having a statistically significant increase over background concentrations and the names of the monitoring wells associated with the increase;

C) Specify whether there have been any exceedances of the groundwater protection standards for one or more constituents listed in Section 845.600;

D) Identify those constituents with exceedances of the groundwater protection standards in Section 845.600 and the names of the monitoring wells associated with the exceedance;

E) Provide the date when the assessment of corrective measures was initiated for the CCR surface impoundment;

F) Provide the date when the assessment of corrective measures was completed for the CCR surface impoundment;

G) Specify whether a remedy was selected under Section 845.670 during the current annual reporting period, and if so, the date of remedy selection; and

H) Specify whether remedial activities were initiated or are ongoing under Section 845.780 during the current annual reporting period.

Section 845.620 Hydrogeologic Site Characterization

a) The owner or operator of the CCR surface impoundment must design and implement a hydrogeologic site characterization.

b) The hydrogeologic site characterization must include, but is not limited to, the following:

1) Geologic well logs/boring logs;

2) Climatic aspects of the site, including seasonal and temporal fluctuations in groundwater flow;

3) Identification of nearby surface water bodies and drinking water intakes;

4) Identification of nearby pumping wells and associated uses of the groundwater;

5) Identification of nearby dedicated nature preserves;

6) Geologic setting;

7) Structural characteristics;

8) Geologic cross-sections;

9) Soil characteristics;

10) Identification of confining layers;

11) Identification of potential migration pathways;

12) Groundwater quality data;

13) Vertical and horizontal extent of the geologic layers to a minimum depth of 100 feet below land surface, including lithology and stratigraphy;

14) A map displaying any known underground mines beneath a CCR surface impoundment;

15) Chemical and physical properties of the geologic layers to a minimum depth of 100 feet below land surface;

16) Hydraulic characteristics of the geologic layers identified as migration pathways and geologic layers that limit migration, including:

    A) Water table depth;

    B) Hydraulic conductivities;

    C) Effective and total porosities;

    D) Direction and velocity of groundwater flow; and

E) Map of the potentiometric surface;

17) Groundwater classification under 35 Ill. Adm. Code 620; and

18) Any other information requested by the Agency that is relevant to the hydrogeologic site characterization.

Section 845.630 Groundwater Monitoring Systems

a) Performance Standard. The owner or operator of a CCR surface impoundment must install a groundwater monitoring system that consists of a sufficient number of wells, installed at appropriate locations and depths, to yield groundwater samples that:

1) Accurately represent the quality of background groundwater that has not been affected by leakage from a CCR surface impoundment. A determination of background quality may include sampling of wells that are not hydraulically upgradient of the CCR management area where:

A) Hydrogeologic conditions do not allow the owner or operator of the CCR surface impoundment to determine what wells are hydraulically upgradient; or

B) Sampling at other wells will provide an indication of background groundwater quality that is demonstratively as representative or more representative than that provided by the upgradient wells; and

2) Accurately represent the quality of groundwater passing the waste boundary of the CCR surface impoundment. The downgradient monitoring system must be installed at the waste boundary that ensures detection of groundwater contamination. All potential contaminant pathways must be monitored.

b) The number, spacing, and depths of monitoring system wells must be determined based upon site-specific technical information identified in the hydrogeologic site characterization conducted under Section 845.620.

c) The groundwater monitoring system must include a sufficient number of monitoring wells necessary to meet the performance standards specified in subsection (a) based on the site-specific information specified in subsection (b). The groundwater monitoring system must contain:

1) A minimum of one upgradient and three downgradient monitoring wells; and

2) Additional monitoring wells as necessary to accurately represent the quality of background groundwater that has not been affected by leakage from the CCR surface impoundment and the quality of groundwater passing the waste boundary of the CCR surface impoundment.

d) Multiunit Groundwater Monitoring System

1) The owner or operator of multiple CCR surface impoundments may install a multiunit groundwater monitoring system instead of separate groundwater monitoring systems for each CCR surface impoundment.

2) The multiunit groundwater monitoring system must be equally as capable of detecting monitored constituents at the waste boundary of the CCR surface impoundment as the individual groundwater monitoring system specified in subsections (a) through (c) for each CCR surface impoundment, based on the following factors:

A) Number, spacing, and orientation of each CCR surface impoundment;

B) Hydrogeologic setting;

C) Site history; and

D) Engineering design of the CCR surface impoundment.

e) Monitoring wells must be properly constructed in a manner consistent with the standards of 77 Ill. Adm. Code 920.170.

1) The owner or operator must document and include in the facility's operating record the design, installation, development, and decommissioning of any monitoring wells, piezometers and other measurement, sampling, and analytical devices. The qualified professional engineer must be given access to this documentation when completing the groundwater monitoring system certification required by subsection (g).

2) The monitoring wells, piezometers, and other measurement, sampling, and analytical devices must be operated and maintained so that they perform to the design specifications throughout the life of the monitoring program.

f) The owner or operator of a new CCR surface impoundment must submit a construction permit application containing documentation showing that the groundwater monitoring system is designed to meet the requirements of this Section. The owner or operator of all CCR surface impoundments must submit an operating permit application containing documentation showing that the groundwater monitoring system has been constructed to meet the requirements of this Section.

g) The owner or operator must obtain a certification from a qualified professional engineer stating that the groundwater monitoring system has been designed and constructed to meet the requirements of this Section. If the groundwater monitoring system includes the minimum number of monitoring wells specified in subsection (c)(1), the certification must document the basis supporting this determination. The certification must be submitted to the Agency with the appropriate permit application.

Section 845.640 Groundwater Sampling and Analysis Requirements

a) The groundwater monitoring program must include consistent sampling and analysis procedures that are designed to ensure monitoring results that provide an accurate representation of groundwater quality at the background and downgradient wells required by Section 845.630. The owner or operator of the CCR surface impoundment must develop a sampling and analysis program that includes procedures and techniques for:

  1) Sample collection;

  2) Sample preservation and shipment;

  3) Analytical procedures;

  4) Chain of custody control; and

  5) Quality assurance and quality control.

b) The groundwater monitoring program must include sampling and analytical methods that are appropriate for groundwater sampling and that accurately measure constituents and other monitoring parameters in groundwater samples. For purposes of this Subpart, the term "constituent" refers to both constituents and other monitoring parameters listed in Section 845.600.

c) The owner or operator must perform the following each time ground water is sampled:

  1) Measure groundwater elevations in each well before purging;

  2) Determine the rate and direction of groundwater flow; and

  3) Measure groundwater elevations in wells that monitor the same CCR management area within a time period short enough to avoid temporal

variations in groundwater flow that could preclude accurate determination of groundwater flow rate and direction.

d) The owner or operator of the CCR surface impoundment must establish background groundwater quality in a hydraulically upgradient or background well for each of the constituents listed in Section 845.600. Background groundwater quality may be established at wells that are not located hydraulically upgradient from the CCR surface impoundment if it meets the requirements of Section 845.630(a)(1).

e) The number of samples collected when conducting monitoring (for both downgradient and background wells) must be consistent with the statistical procedures chosen under subsection (f) and the performance standards under subsection (g). The sampling procedures must be those specified by Section 845.650(a) through (c).

f) Statistical Methods

1) The owner or operator of the CCR surface impoundment must select one of the statistical methods specified in subsection (f)(1) to be used in evaluating groundwater monitoring data for each specified constituent. The statistical test chosen must be conducted separately for each constituent in each monitoring well.

A) A parametric analysis of variance followed by multiple comparison procedures to identify statistically significant evidence of contamination. The method must include estimation and testing of the contrasts between each compliance well's mean and the background mean levels for each constituent.

B) An analysis of variance based on ranks followed by multiple comparison procedures to identify statistically significant evidence of contamination. The method must include estimation and testing of the contrasts between each compliance well's median and the background median levels for each constituent.

C) A tolerance or prediction interval procedure, in which an interval for each constituent is established from the distribution of the background data and the level of each constituent in each compliance well is compared to the upper tolerance or prediction limit.

D) A control chart approach that gives control limits for each constituent.

E) Another statistical test method that meets the performance standards of subsection (g).

2) The owner or operator of the CCR surface impoundment must obtain a certification from a qualified professional engineer stating that the selected statistical method is appropriate for evaluating the groundwater monitoring data for the CCR surface impoundment. The certification must include a narrative description of the statistical method selected to evaluate the groundwater monitoring data. The certification must be submitted to the Agency with the appropriate permit application.

3) The owner or operator of the CCR surface impoundment must submit the following to the Agency in an operating permit application:

A) Documentation of the statistical method chosen; and

B) The qualified professional engineer certification required by subsection (f)(2).

g) Any statistical method chosen under subsection (f) must comply with the following performance standards, as appropriate, based on the statistical test method used:

1) The statistical method used to evaluate groundwater monitoring data must be appropriate for the distribution of constituents. Normal distributions of data values must use parametric methods. Non-normal distributions must use non-parametric methods. If the distribution of the constituents is shown by the owner or operator of the CCR surface impoundment to be inappropriate for a normal theory test, then the data must be transformed or a distribution-free (non-parametric) theory test must be used. If the distributions for the constituents differ, more than one statistical method may be needed.

2) If an individual well comparison procedure is used to compare an individual compliance well constituent concentration with background constituent concentrations or a groundwater protection standard, the test must be done at a Type I error level of at least 0.01 for each testing period. If a multiple comparison procedure is used, the Type I experiment wise error rate for each testing period must be at least 0.05; however, the Type I error of at least 0.01 for individual well comparisons must be maintained. This performance standard does not apply to tolerance intervals, prediction intervals, or control charts.

3) If a control chart approach is used to evaluate groundwater monitoring data, the specific type of control chart and its associated constituent values must be such that this approach is at least as effective as any other

approach in this Section for evaluating groundwater data. The constituent values must be determined after considering the number of samples in the background database, the data distribution, and the range of the concentration values for each constituent of concern.

4) If a tolerance interval or a prediction interval is used to evaluate groundwater monitoring data, the levels of confidence and, for tolerance intervals, the percentage of the population that the interval must contain, must be such that this approach is at least as effective as any other approach in this Section for evaluating groundwater data. These constituents must be determined after considering the number of samples in the background database, the data distribution, and the range of the concentration values for each constituent of concern.

5) The statistical method must account for data below the limit of detection with one or more statistical procedures at least as effective as any other approach in this Section for evaluating groundwater data. Any practical quantitation limit that is used in the statistical method must be the lowest concentration level that can be reliably achieved within specified limits of precision and accuracy during routine laboratory operating conditions that are available to the facility. For the constituents identified in Section 845.600(a)(1), the practical quantitation limit must be less than the groundwater protection standards.

6) If necessary, the statistical method must include procedures to control or correct for seasonal and spatial variability as well as temporal correlation in the data.

h) The owner or operator of the CCR surface impoundment must determine whether there is a statistically significant increase over background values for each constituent in Section 845.600.

1) In determining whether a statistically significant increase has occurred, the owner or operator must compare the groundwater quality of each constituent at each monitoring well designated under Section 845.630(a)(2) or (d)(1) to the background value of that constituent, according to the statistical procedures and performance standards specified by subsections (f) and (g).

2) Within 60 days after completing sampling and analysis, the owner or operator must determine whether there has been a statistically significant increase over background for any constituent at each monitoring well.

i) The owner or operator must measure total recoverable metals concentrations in measuring groundwater quality. Measurement of total recoverable metals captures both the particulate fraction and dissolved fraction of metals in natural waters. Groundwater samples must not be field filtered before analysis.

j) All groundwater samples taken under this Subpart must be analyzed by a certified laboratory using Test Methods for Evaluating Solid Waste, Physical/Chemical Methods, SW-846, incorporated by reference in Section 845.150.

Section 845.650 Groundwater Monitoring Program

a) The owner or operator of a CCR surface impoundment must conduct groundwater monitoring consistent with this Section. At a minimum, groundwater monitoring must include groundwater monitoring for all constituents with a groundwater protection standard in Section 845.600(a), calcium, and turbidity. The owner or operator of the CCR surface impoundment must submit a groundwater monitoring plan to the Agency with its operating permit application.

b) Monitoring Frequency

1) The monitoring frequency for all constituents with a groundwater protection standard in Section 845.600(a), calcium, and turbidity must be at least quarterly during the active life of the CCR surface impoundment and the post-closure care period or period specified in Section 845.740(b) when closure is by removal except as allowed in subsection (b)(4).

A) For existing CCR surface impoundments, a minimum of eight independent samples from each background and downgradient well must be collected and analyzed for all constituents with a groundwater protection standard listed in Section 845.600(a), calcium, and turbidity within 180 days after April 21, 2021.

B) For new CCR surface impoundments, and all lateral expansions of CCR surface impoundments, a minimum of eight independent samples for each background well and downgradient well must be collected and analyzed for all constituents with a groundwater protection standard listed in Section 845.600(a), calcium, and turbidity during the first 180 days of sampling.

2) The groundwater elevation monitoring frequency must be monthly.

3) Measurement of water elevation within the CCR surface impoundment must be conducted each time the groundwater elevations are measured (see subsection 845.650(b)(2)) before dewatering for closure.

4) After completion of five years of monitoring under this Part, the owner or operator of a CCR surface impoundment may ask the Agency for approval

of a semiannual monitoring frequency by demonstrating all of the following:

A) The groundwater monitoring effectiveness will not be compromised by the reduced frequency of monitoring;

B) Sufficient data has been collected to characterize groundwater;

C) The groundwater monitoring schedule currently does not show any statistically significant increasing trends; and

D) The concentrations of constituents monitored under Section 845.650(a) at the down-gradient monitoring wells are below the applicable groundwater protection standards of Section 845.600.

5) If, after an Agency approval of a semiannual monitoring frequency under subsection (b)(4), a statistically significant increasing trend is detected or an exceedance above the GWPS is detected, the monitoring must revert to a quarterly frequency.

c) The number of samples collected and analyzed for each background well and downgradient well during subsequent quarterly sampling events must be consistent with Section 845.640 and must account for any unique characteristics of the site; but must include at least one sample from each background and downgradient well.

d) If one or more constituents are detected, and confirmed by an immediate resample, to be in exceedance of the groundwater protection standards in Section 845.600 in any sampling event, the owner or operator must notify the Agency which constituent exceeded the groundwater protection standard and place the notification in the facility's operating record as required by Section 845.800(d)(16). The owner or operator of the CCR surface impoundment also must:

1) Characterize the nature and extent of the release and any relevant site conditions that may affect the remedy ultimately selected. The characterization must be sufficient to support a complete and accurate assessment of the corrective measures necessary to effectively clean up all releases from the CCR surface impoundment under Section 845.660. The owner or operator of the CCR surface impoundment must submit the characterization to the Agency and place the characterization in the facility's operating record as required by Section 845.800(d)(16). Characterization of the release includes the following minimum measures:

A) Install additional monitoring wells necessary to define the contaminant plumes;

B) Collect data on the nature and estimated quantity of material released, including specific information on the constituents listed in Section 845.600 and the levels at which they are present in the material released;

C) Install at least one additional monitoring well at the facility boundary in the direction of contaminant migration and sample this well in accordance with subsections (a) and (b); and

D) Sample all wells in accordance with subsections (a) and (b) to characterize the nature and extent of the release.

2) Notify all persons who own the land or reside on the land that directly overlies any part of the plume of contamination if contaminants have migrated off-site as indicated by sampling of wells in accordance with subsection (d)(1). The owner or operator must send notifications made under this subsection (d)(2) to the Agency and place the notifications in the facility's operating record (see Section 845.800(d)(16)).

3) Except as provided in subsection (e), within 90 days after the detected exceedance of the groundwater protection standard, initiate an assessment of corrective measures (see Section 845.660).

e) Alternative Source Demonstration (ASD). The owner or operator of a CCR surface impoundment may, within 60 days after the detected exceedance of the groundwater protection standard, submit a demonstration to the Agency that a source other than the CCR surface impoundment caused the contamination and the CCR surface impoundment did not contribute to the contamination, or that the exceedance of the groundwater protection standard resulted from error in sampling, analysis, statistical evaluation, natural variation in groundwater quality, or a change in the potentiometric surface and groundwater flow direction. Either type of ASD must include a report that contains the factual or evidentiary basis for any conclusions and a certification of accuracy by a qualified professional engineer.

1) The owner or operator must place the ASD on the facility's publicly accessible Internet site (CCR website) under Section 845.810 within 24 hours after the submission to the Agency.

2) Within two business days after receiving the ASD, the Agency must email a notice to its listserv for the facility that the ASD is available to view on the facility's CCR website.

3) Members of the public may submit to the Agency written comments on the ASD within 14 days after the Agency provides notice under subsection (e)(2).

4) The Agency must provide a written response to the owner and operator either concurring or not concurring with the ASD within 30 days after receiving the ASD. The Agency must also mail or email its response to each person who timely submitted a written public comment under subsection (e)(3) and supplied a mailing or email address.

5) If the Agency concurs with the ASD, the owner or operator must continue monitoring as required by this Section. The owner or operator must also include the ASD in the annual groundwater monitoring and corrective action report required by Section 845.610(e).

6) If the Agency does not concur with the ASD, the owner or operator must initiate the assessment of corrective measures under Section 845.660.

7) If the Agency does not concur with the ASD, the owner or operator may petition the Board for review of the Agency's non-concurrence under 35 Ill. Adm. Code 105. The filing of a petition for review under subsection (e)(7) does not automatically stay any requirements of this Part as to the owner or operator, including the 90-day deadline to initiate an assessment of corrective measures (see Section 845.660(a)(1)).

Section 845.660 Assessment of Corrective Measures

a) Unless the Agency has concurred with an alternative source demonstration made under Section 845.650(e), the owner or operator must initiate an assessment of corrective measures to prevent further releases, to remediate any releases, and to restore the affected area.

1) The assessment of corrective measures must be initiated within 90 days after finding that any constituent listed in Section 845.600 has been detected in exceedance of the groundwater protection standards in Section 845.600, at the downgradient waste boundary or immediately upon detection of a release of CCR from a CCR surface impoundment.

2) The assessment of corrective measures must be completed and submitted to the Agency within 90 days after initiation of assessment of corrective measures, unless the owner or operator demonstrates to the Agency the need for additional time to complete the assessment of corrective measures due to site-specific conditions or circumstances. The owner or operator must submit this demonstration, along with a certification from a qualified professional engineer attesting that the demonstration is accurate, to the Agency within 60 days after initiating an assessment of corrective

measures. The Agency must either approve or disapprove the demonstration within 30 days. The 90-day deadline to complete the assessment of corrective measures may be extended for no longer than 60 days. The owner or operator must also include the Agency approved demonstration in the annual groundwater monitoring and corrective action report required by Section 845.610(e), in addition to the certification by a qualified professional engineer.

b) The owner or operator of the CCR surface impoundment must continue to monitor groundwater in accordance with the monitoring program as specified in Section 845.650.

c) The assessment under subsection (a) must include an analysis of the effectiveness of potential corrective measures in meeting all the requirements and objectives of the corrective action plan, as described by Section 845.670, addressing at least the following:

  1) The performance, reliability, ease of implementation, and potential impacts of appropriate potential remedies, including safety impacts, cross-media impacts, and control of exposure to any residual contamination;

  2) The time required to begin and complete the corrective action plan; and

  3) The institutional requirements, such as State or local permit requirements or other environmental or public health requirements that may substantially affect implementation of the corrective action plan.

d) The owner or operator of the CCR surface impoundment must discuss the results of the corrective measures assessment, at least 30 days before the selection of remedy, in a public meeting with interested and affected parties (see Section 845.240).

e) When the owner or operator of a CCR surface impoundment is completing closure and corrective action simultaneously, the owner or operator may combine the corrective measures assessment required by this Section and the closure alternatives analysis required by Section 845.710 into one assessment of alternatives.

Section 845.670 Corrective Action Plan

a) The owner or operator must prepare a semi-annual report describing the progress in selecting a remedy and developing a corrective action plan. The semi-annual report must be submitted to the Agency and placed in the operating record as required by Section 845.800(d)(17).

b) Within one year after completing the assessment of corrective measures as specified in Section 845.660, and after completion of the public meeting in Section 845.660(d), the owner or operator of the CCR surface impoundment must submit, in a construction permit application to the Agency, a corrective action plan that identifies the selected remedy. This requirement applies in addition to, not in place of, any applicable standards under any other State or federal law.

c) The corrective action plan must meet the following requirements:

1) Be based on the results of the corrective measures assessment conducted under Section 845.660;

2) Identify a selected remedy that at a minimum, meets the standards listed in subsection (d);

3) Contain the corrective action alternatives analysis specified in subsection (e); and

4) Contain proposed schedules for implementation, including an analysis of the factors in subsection (f);

d) The selected remedy in the corrective action plan must:

1) Be protective of human health and the environment;

2) Attain the groundwater protection standards specified in Section 845.600;

3) Control the sources of releases to reduce or eliminate, to the maximum extent feasible, further releases of constituents listed in Section 845.600 into the environment;

4) Remove from the environment as much of the contaminated material that was released from the CCR surface impoundment as is feasible, taking into account factors such as avoiding inappropriate disturbance of sensitive ecosystems; and

5) Comply with standards for management of wastes as specified in Section 845.680(d).

e) Corrective Action Alternatives Analysis. In selecting a remedy that meets the standards of subsection (d), the owner or operator of the CCR surface impoundment must consider the following evaluation factors:

1) The long- and short-term effectiveness and protectiveness of each potential remedy, along with the degree of certainty that the remedy will prove successful based on consideration of the following:

A) Magnitude of reduction of existing risks;

B) Magnitude of residual risks in terms of likelihood of further releases due to CCR remaining following implementation of a remedy;

C) The type and degree of long-term management required, including monitoring, operation, and maintenance;

D) Short-term risks that might be posed to the community or the environment during implementation of a remedy, including potential threats to human health and the environment associated with excavation, transportation, and re-disposal of contaminants;

E) Time until groundwater protection standards in Section 845.600 are achieved;

F) The potential for exposure of humans and environmental receptors to remaining wastes, considering the potential threat to human health and the environment associated with excavation, transportation, re-disposal, containment, or changes in groundwater flow;

G) The long-term reliability of the engineering and institutional controls, including an analysis of any off-site, nearby destabilizing activities; and

H) Potential need for replacement of the remedy.

2) The effectiveness of the remedy in controlling the source to reduce further releases based on consideration of each of the following potential factors:

A) The extent to which containment practices will reduce further releases; and

B) The extent to which treatment technologies may be used.

3) The ease or difficulty of implementing each potential remedy based on consideration of the following types of factors:

A) Degree of difficulty associated with constructing the technology;

B) Expected operational reliability of the technologies;

    C) Need to coordinate with and obtain necessary approvals and permits from other agencies;

    D) Availability of necessary equipment and specialists; and

    E) Available capacity and location of needed treatment, storage, and disposal services.

  4) The degree to which community concerns are addressed by each potential remedy.

f) The owner or operator must specify, as part of the corrective action plan, a schedule for implementing, of and completing, remedial activities. The schedule must require the completion of remedial activities within a reasonable time, taking into consideration the factors in this subsection (f). The owner or operator of the CCR surface impoundment must consider the following factors in determining the schedule of remedial activities:

  1) Extent and nature of contamination, as determined by the characterization required under Section 845.650(d);

  2) Reasonable probabilities of remedial technologies achieving compliance with the groundwater protection standards established by Section 845.600 and other objectives of the remedy;

  3) Availability of treatment or disposal capacity for CCR managed during implementation of the remedy;

  4) Potential risks to human health and the environment from exposure to contamination before completion of the remedy;

  5) Resource value of the aquifer, including:

    A) Current and future uses, including potential residential, agricultural, commercial industrial and ecological uses;

    B) Proximity and withdrawal rate of users;

    C) Groundwater quantity and quality;

    D) The potential impact to the subsurface ecosystem, wildlife, other natural resources, crops, vegetation, and physical structures caused by exposure to CCR constituents;

    E) The hydrogeologic characteristic of the facility and surrounding land; and

F) The availability of alternative water supplies; and

6) Other relevant factors.

Section 845.680 Implementation of the Corrective Action Plan

a) Within 90 days after the Agency's approval of the corrective action plan submitted under Section 845.670, the owner or operator must initiate corrective action. Based on the schedule approved by the Agency for implementation and completion of corrective action, the owner or operator must:

1) Establish and implement a corrective action groundwater monitoring program that:

A) At a minimum, meets the requirements of the monitoring program under Section 845.650;

B) Documents the effectiveness of the corrective action remedy; and

C) Demonstrates compliance with the groundwater protection standard under subsection (c).

2) Implement the corrective action remedy approved by the Agency under Section 845.670; and

3) Take any interim measures necessary to reduce the contaminants leaching from the CCR surface impoundment, and/or potential exposures to human or ecological receptors. Interim measures must, to the greatest extent feasible, be consistent with the objectives of, and contribute to the performance of, any remedy that may be required by Section 845.670. The following factors must be considered by an owner or operator in determining whether interim measures are necessary:

A) Time required to develop and implement a final remedy;

B) Actual or potential exposure of nearby populations or environmental receptors to any of the constituents listed in Section 845.600;

C) Actual or potential contamination of sensitive ecosystems or current or potential drinking water supplies;

D) Further degradation of the groundwater that may occur if remedial action is not initiated expeditiously;

E) Weather conditions that may cause any of the constituents listed in Section 845.600 to migrate or be released;

F) Potential for exposure to any of the constituents listed in Section 845.600 as a result of an accident or failure of a container or handling system; and

G) Other situations that may pose threats to human health and the environment.

b) If the Agency or an owner or operator of the CCR surface impoundment determines, at any time, that compliance with the requirements of Section 845.670(d) is not being achieved through the remedy selected, the owner or operator must implement other methods or techniques that could feasibly achieve compliance with the requirements. These methods or techniques must receive approval by the Agency before implementation.

c) Corrective action must be considered complete when:

1) The owner or operator of the CCR surface impoundment demonstrates compliance with the groundwater protection standards established by Section 845.600 has been achieved at all points within the plume of contamination that lies beyond the waste boundary;

2) Compliance with the groundwater protection standards has been achieved by demonstrating that concentrations of constituents listed in Section 845.600 have not exceeded the groundwater protection standards for a period of three consecutive years, using the statistical procedures and performance standards in Section 845.640(f) and (g); and

3) All actions required to complete the remedy have been satisfied.

d) All CCR managed under a remedy approved by the Agency under Section 845.670, or an interim measure required under subsection (a)(3), must be managed in a manner that complies with this Part.

e) Upon completion of the corrective action plan, the owner or operator must submit to the Agency a corrective action completion report and certification.

1) The corrective action completion report must contain supporting documentation, including:

A) Any engineering and hydrogeology reports, including, monitoring well completion reports and boring logs, all CQA reports, certifications, and designations of CQA officers-in-absentia required by Section 845.290;

B) A written summary of the implementation of the corrective action plan as stated in the construction permit and this Part;

C) Groundwater monitoring data demonstrating compliance with subsection (c);

D) Any remedial actions completed under subsection(d);

E) Documentation showing compliance with the selected remedy requirements of Section 845.670(b); and

F) Any other information relied upon by the qualified professional engineer in making the closure certification.

2) The corrective action completion certification must include a statement from a qualified professional engineer attesting that the corrective action plan has been completed in compliance with the requirements of subsection (c).

3) The owner or operator must place the corrective action completion report and certification in the facility's operating record as required by Section 845.800(d)(18).

SUBPART G: CLOSURE AND POST-CLOSURE CARE

Section 845.700 Required Closure or Retrofit of CCR Surface Impoundments

a) Required Closure. The owner or operator of the following CCR surface impoundments must stop placing CCR or non-CCR waste streams in the CCR surface impoundment and must initiate closure of the CCR surface impoundment:

1) An existing CCR surface impoundment that has not demonstrated compliance with any of the following location restrictions:

A) Uppermost aquifer location (see Section 845.300);

B) Wetlands (see Section 845.310);

C) Fault areas (see Section 845.320);

D) Seismic impact zones (see Section 845.330); or

E) Unstable areas and floodplains (see Section 845.340).

2) The owner or operator of any CCR surface impoundment that has failed to complete the initial or any subsequent annual safety factor assessment required by Section 845.460 or that has failed to document the calculated factors of safety for the CCR surface impoundment to achieve the minimum safety factors specified in Section 845.460(a).

b) Required Closure or Retrofit. The owner or operator of an existing unlined CCR surface impoundment, as determined under Section 845.400(f), must stop placing CCR and non-CCR waste streams into that CCR surface impoundment and either retrofit or close the CCR surface impoundment in accordance with the requirements of Subpart G. The owner or operator of a CCR surface impoundment electing to retrofit must submit, in accordance with the schedule in subsection (h), the written preliminary retrofit plan under subsection 845.770(a)(3) and a construction permit application to retrofit under Section 845.770;

c) Beginning on April 21, 2021, the owner or operator of the CCR surface impoundment required to close under subsection (a), or electing to close under subsection (b), must immediately take steps to categorize the CCR surface impoundment under subsection (g) and to comply with the closure alternatives analysis requirements in Section 845.710. Within 30 days after April 21, 2021, the owner or operator must send the category designation, including a justification for the category designation, for each CCR surface impoundment to the Agency for review. The owner or operator of the CCR surface impoundment must submit a construction permit application containing a final closure plan under the schedule in subsection (h).

d) Timeframes for Closure

1) Except as provided in subsection (d)(2), the owner or operator must stop placing CCR and non-CCR waste streams in the impoundment and initiate closure within six months after failing to complete any of the demonstrations listed in subsection (a).

2) For CCR surface impoundments required to close under subsection (a)(1) or electing to close under subsection (b):

A) If, on April 21, 2021, the owner or operator of a CCR surface impoundment has not satisfied an alternative closure requirement of 40 CFR 257.103 that allows for the continued receipt of CCR or non-CCR waste streams, the owner or operator must not place CCR or non-CCR waste streams into the CCR surface impoundment after April 21, 2021.

B) If, by November 30, 2020, the owner or operator of a CCR surface impoundment has submitted a complete demonstration to USEPA seeking an alternative deadline to stop receiving waste or complete closure under 40 CFR 257.103(f), the deadline to stop receiving waste will be tolled until USEPA issues a decision. If USEPA determines that a submission is incomplete, an owner or operator must immediately stop receiving waste and comply with all applicable deadlines of Section 845.700(d)(1).

C) If USEPA disapproves the requested alternative deadline to stop receiving waste and complete closure, the owner or operator of the CCR surface impoundment must immediately stop receiving waste and initiate closure within six months after the USEPA denial of the extension and will be subject to Section 845.760(a).

D) If, USEPA approves a demonstration that alternative disposal capacity is infeasible under 40 CFR 257.103(f)(1), the owner or operator must stop placing CCR or non-CCR waste streams into the CCR surface impoundment by the end of the initial time extension approved under 40 CFR 257.103 or once alternative capacity becomes available, whichever is sooner. In no case may the owner or operator of the CCR surface impoundment place CCR or non-CCR waste streams into an eligible CCR surface impoundment after October 15, 2024, or into any other CCR surface impoundment subject to closure under Section 845.700(a) or (b) after October 15, 2023.

E) If USEPA approves a demonstration for permanent cessation of coal-fired power boilers by a certain date under 40 CFR 257.103(f)(2), the owner or operator must:

  i) For CCR surface impoundments that are 40 acres or smaller, stop operation of the coal-fired boiler and complete closure by October 17, 2023; or

  ii) For CCR surface impoundments that are larger than 40 acres, stop operation of the coal-fired boiler and complete closure by October 17, 2028.

F) The USEPA's decision to approve or deny the demonstration requesting an alternative deadline to initiate closure must, within 30 days be submitted to the Agency and placed in the facility’s operating record as required by Section 845.800(d)(19).

G) Failure to remain in compliance with any of the requirements of this Part will result in the automatic loss of authorization under subsections (d)(2)(D) and (d)(2)(E).

H) The owner or operator of the CCR surface impoundment with a USEPA-approved extension will not be given extensions of the timeframes for completion of closure under Section 845.760(c).

e) Semi-Annual Reports. The owner or operator of a CCR surface impoundment closing under the time frames in subsections (d)(2)(B) and (d)(2)(C) must prepare semi-annual reports consistent with the requirements in 40 CFR 257.103(f)(1)(x), incorporated by reference in Section 845.150, until the owner or operator has initiated closure.

f) An owner or operator of a CCR surface impoundment required to close under this Section must prepare the notification required under Section 845.730(d) that the CCR surface impoundment is closing under this Section.

g) Closure Prioritization

1) The owner or operator of a CCR surface impoundment required to close under this Section must assign the CCR surface impoundment to one of the following categories. Category 1 has the highest priority for closure. Category 7 has the lowest priority for closure.

A) Category 1 includes CCR surface impoundments that have impacted an existing potable water supply well or that have impacted groundwater quality within the setback of an existing potable water supply well.

B) Category 2 includes CCR surface impoundments that are an imminent threat to human health or the environment or have been designated by the Agency under subsection (g)(5).

C) Category 3 includes CCR surface impoundments located in areas of environmental justice concern, as determined by the Agency under subsection (g)(6).

D) Category 4 includes inactive CCR surface impoundments that have an exceedance of the groundwater protection standards in Section 845.600.

E) Category 5 includes existing CCR surface impoundments that have exceedances of the groundwater protection standards in Section 845.600.

F) Category 6 includes inactive CCR surface impoundments that are in compliance with the groundwater protection standards in Section 845.600.

G) Category 7 includes existing CCR surface impoundments that are in compliance with the groundwater protection standards in Section 845.600.

2) If a CCR surface impoundment can be categorized in more than one category, the owner or operator of the CCR surface impoundment must assign the CCR surface impoundment the highest priority category.

3) Whenever an owner or operator of a CCR surface impoundment has more than one CCR surface impoundment that must close under this Section, the owner or operator must close the CCR surface impoundments in order of priority.

4) If the CCR surface impoundment meets the criteria for Category 1, the owner or operator must take immediate steps to mitigate the impact to any existing potable water supply. The owner or operator of the CCR surface impoundment, must act to replace the water supply with a supply of equal or better quality and quantity within 30 days after notice that the impact has occurred.

5) The Agency may designate a CCR surface impoundment as a Category 2 surface impoundment when:

A) The CCR surface impoundment has failed to document that the calculated factors of safety for the CCR surface impoundment achieve the minimum safety factors specified in Section 845.460(a);

B) The CCR surface impoundment has not demonstrated compliance with the location restrictions in Subpart C;

C) The owner or operator has been enjoined under Section 43 of the Act;

D) An exceedance of the groundwater protection standards in Section 845.600 has migrated off-site; or

E) The Agency finds that an emergency condition exists creating an immediate danger to public health or welfare, or the environment.

6) For purposes of, and only for, this Part, areas of environmental justice concern are identified as any area that meets either of the following:

A) Any area within one mile of a census block group where the number of low-income persons is twice the statewide average, where low income means the number or percent of a census block group's population in households where the household income is less than or equal to twice the federal poverty level; or

B) Any area within one mile of a census block group where the number of minority persons is twice the statewide average, where minority means the number or percent of individuals in a census block group who list their racial status as a race other than white alone or list their ethnicity as Hispanic or Latino.

7) For purposes of subsection (g)(6), if any part of a facility falls within one mile of the census block group, the entire facility, including all its CCR surface impoundments, must be considered an area of environmental justice concern.

8) The Agency may designate a CCR surface impoundment as another Category when site-specific conditions contradict the designations provided by the owner or operator in subsection (c) and the categories in subsection (g)(1).

h) Application Schedule

1) Category 1, Category 2, Category 3, and Category 4 CCR surface impoundment owners or operators must submit either a construction permit application containing a final closure plan or a construction permit application to retrofit the CCR surface impoundment in accordance with the requirements of this Part by February 1, 2022.

2) Category 5 CCR surface impoundment owners or operators must submit either a construction permit application containing a final closure plan or a construction permit application to retrofit the CCR surface impoundment in accordance with the requirements of this Part by August 1, 2022.

3) Category 6 and Category 7 CCR surface impoundment owners or operators must submit either a construction permit application containing a final closure plan or a construction permit application to retrofit the CCR surface impoundment in accordance with the requirements of this Part by August 1, 2023.

4) Owners or operators consolidating one or more CCR surface impoundments for closure must meet the application schedule of the highest priority CCR surface impoundment.

5) If the Agency denies a construction permit application submitted under this Section, the owner and operator must submit a revised construction permit application addressing all deficiencies identified by the Agency. The revised construction permit application for closure must be submitted

to the Agency within 90 days after the Agency's denial if the Agency's denial is not appealed under Section 845.270. If the Agency's denial is appealed and upheld, the owner or operator must submit a revised construction permit application for closure within 90 days after a final decision by the Board is rendered. The owner or operator of the CCR surface impoundment must discuss the owner's or operator's proposed response to all deficiencies identified by the Agency in a public meeting with interested and affected parties held under Section 845.240.

Section 845.710 Closure Alternatives

a) Closure of a CCR surface impoundment, or any lateral expansion of a CCR surface impoundment, must be completed either by leaving the CCR in place and installing a final cover system or through removal of the CCR and decontamination of the CCR surface impoundment, as described in Sections 845.720 through 845.760.

b) Before selecting a closure method, the owner or operator of each CCR surface impoundment must complete a closure alternatives analysis. The closure alternatives analysis must examine the following for each closure alternative:

1) The long- and short-term effectiveness and protectiveness of the closure method, including identification and analyses of the following factors:

A) The magnitude of reduction of existing risks;

B) The magnitude of residual risks in terms of likelihood of future releases of CCR;

C) The type and degree of long-term management required, including monitoring, operation, and maintenance;

D) The short-term risks that might be posed to the community or the environment during implementation of a closure, including potential threats to human health and the environment associated with excavation, transportation, and re-disposal of contaminants;

E) The time until closure and post-closure care or the completion of groundwater monitoring under Section 845.740(b) is completed;

F) The potential for exposure of humans and environmental receptors to remaining wastes, considering the potential threat to human health and the environment associated with excavation, transportation, re-disposal, containment or changes in groundwater flow;

G) The long-term reliability of the engineering and institutional controls, including an analysis of any off-site, nearby destabilizing activities; and

H) Potential need for future corrective action of the closure alternative.

2) The effectiveness of the closure method in controlling future releases based on analyses of the following factors:

A) The extent to which containment practices will reduce further releases; and

B) The extent to which treatment technologies may be used.

3) The ease or difficulty of implementing a potential closure method based on analyses of the following types of factors:

A) Degree of difficulty associated with constructing the technology;

B) Expected operational reliability of the technologies;

C) Need to coordinate with and obtain necessary approvals and permits from other agencies;

D) Availability of necessary equipment and specialists; and

E) Available capacity and location of needed treatment, storage, and disposal services.

4) The degree to which the concerns of the residents living within communities where the CCR will be handled, transported and disposed of are addressed by the closure method.

c) In the closure alternatives analysis, the owner or operator of the CCR surface impoundment must:

1) Analyze complete removal of the CCR as one closure alternative, along with the modes for transporting the removed CCR, including by rail, barge, low-polluting trucks, or a combination of these transportation modes;

2) Identify whether the facility has an onsite landfill with remaining capacity that can legally accept CCR, and, if not, whether constructing an onsite landfill is possible; and

3) Include any other closure method in the alternatives analysis if requested by the Agency.

d) The analysis for each alternative completed under this Section must:

1) Meet or exceed a class 4 estimate under the AACE Classification Standard, incorporated by reference in Section 845.150, or a comparable classification practice as provided in the AACE Classification Standard;

2) Contain the results of groundwater contaminant transport modeling and calculations showing how the closure alternative will achieve compliance with the applicable groundwater protection standards;

3) Include a description of the fate and transport of contaminants with the closure alternative over time, including consideration of seasonal variations; and

4) Assess impacts to waters in the State.

e) At least 30 days before submission of a construction permit application for closure, the owner or operator of the CCR surface impoundment must discuss the results of the closure alternatives analysis in a public meeting with interested and affected parties (see Section 845.240).

f) After completion of the public meeting under subsection (e), the owner or operator of a CCR surface impoundment must select a closure method and submit a final closure plan to the Agency under Section 845.720(b). All materials demonstrating completion of the closure alternatives analysis specified in this Section must be submitted with the final closure plan.

g) The selected closure method must meet the requirements and standards of this Part, ensure the protection of human health and the environment, and achieve compliance with the groundwater protection standards in Section 845.600.

Section 845.720 Closure Plan

a) Preliminary Written Closure Plan

1) Content of the Preliminary Closure Plan. The owner or operator of a new CCR surface impoundment or an existing CCR surface impoundment not required to close under Section 845.700 must prepare a preliminary written closure plan that describes the steps necessary to close the CCR surface impoundment at any point during the active life of the CCR surface impoundment consistent with recognized and generally accepted engineering practices. The preliminary written closure plan must include, at a minimum, the following:

A) A narrative description of how the CCR surface impoundment will be closed in accordance with this Part.

B) If closure of the CCR surface impoundment will be accomplished through removal of CCR from the CCR surface impoundment, a description of the procedures to remove the CCR and decontaminate the CCR surface impoundment in accordance with Section 845.740.

C) If closure of the CCR surface impoundment will be accomplished by leaving CCR in place, a description of the final cover system, designed in accordance with Section 845.750, and the methods and procedures to be used to install the final cover. The closure plan must also discuss how the final cover system will achieve the performance standards specified in Section 845.750.

D) An estimate of the maximum inventory of CCR ever on-site over the active life of the CCR surface impoundment.

E) An estimate of the largest area of the CCR surface impoundment ever requiring a final cover (see Section 845.750), at any time during the CCR surface impoundment's active life.

F) A schedule for completing all activities necessary to satisfy the closure criteria in this Section, including an estimate of the year in which all closure activities for the CCR surface impoundment will be completed. The schedule should provide sufficient information to describe the sequential steps that will be taken to close the CCR surface impoundment, including identification of major milestones such as coordinating with and obtaining necessary approvals and permits from other agencies, the dewatering and stabilization phases of CCR surface impoundment closure, or installation of the final cover system, and the estimated timeframes to complete each step or phase of CCR surface impoundment closure. When preparing the preliminary written closure plan, if the owner or operator of a CCR surface impoundment estimates that the time required to complete closure will exceed the timeframes specified in Section 845.760(a), the preliminary written closure plan must include the site-specific information, factors and considerations that would support any time extension sought under Section 845.760(b).

2) The owner or operator of the CCR surface impoundment must submit the preliminary written closure plan to the Agency with its initial operating permit application. The owner or operator of the CCR surface

impoundment must submit the most recently amended preliminary closure plan to the Agency with each operating permit renewal application. The owner or operator must place preliminary and amended preliminary written closure plans in the facility's operating record as required by Section 845.800(d)(20).

3) Amendment of a Preliminary Written Closure Plan.

A) The owner or operator may amend the preliminary written closure plan at any time.

B) The owner or operator must amend the preliminary written closure plan whenever:

i) There is a change in the operation of the CCR surface impoundment that would substantially affect the written closure plan in effect; or

ii) Before closure activities have started, unanticipated events necessitate a revision of the written closure plan.

C) The owner or operator must amend the closure plan at least 60 days before a planned change in the operation of the facility or CCR surface impoundment, or within 60 days after an unanticipated event requires the need to revise an existing written closure plan.

4) The owner or operator of the CCR surface impoundment must obtain and submit with its initial and renewal operating permit applications a written certification from a qualified professional engineer that the initial and any amendment of the preliminary written closure plan meets the requirements of this Part.

b) Final Closure Plan

1) The owner or operator of a CCR surface impoundment must submit to the Agency, as a part of a construction permit application for closure, a final closure plan. The plan must be submitted before the installation of a final cover system or removal of CCR from the surface impoundment for the purpose of closure.

2) Except as otherwise provided in Section 22.59 of the Act, the owner or operator of a CCR surface impoundment must not close a CCR surface impoundment without a construction permit issued under this Part.

3) The final closure plan must identify the proposed selected closure method, and must include the information required in subsection (a)(1) and the closure alternatives analysis specified in Section 845.710.

4) If a final written closure plan revision is necessary after closure activities have started for a CCR surface impoundment, the owner or operator must submit a request to modify the construction permit within 60 days following the triggering event.

5) The owner or operator of the CCR surface impoundment must obtain and submit with its construction permit application for closure a written certification from a qualified professional engineer that the final written closure plan meets the requirements of this Part.

Section 845.730 Initiation of Closure

Initiation of closure activities. Except as provided for in this Section, the owner or operator of a CCR surface impoundment must initiate closure of the CCR surface impoundment within the applicable timeframes specified in either subsection (a) or (b). For purposes of this Section, closure of the CCR surface impoundment has been initiated if the owner or operator has stopped placing waste in the CCR surface impoundment and has submitted to the Agency a construction permit application under Section 845.220(d).

a) Known Final Receipt. The owner or operator must initiate closure of the CCR surface impoundment within 30 days after the date on which the CCR surface impoundment either:

1) Receives the known final placement of waste, either CCR or any non-CCR waste stream; or

2) Removes the known final volume of CCR from the CCR surface impoundment for the purpose of beneficial use of CCR.

b) Temporarily Idled CCR Surface Impoundments.

1) Except as provided by subsection (b)(2), the owner or operator must initiate closure of a CCR surface impoundment that has not received CCR or any non-CCR waste stream, or is no longer removing CCR for the purpose of beneficial use, within two years after the last receipt of waste or within two years after the last removal of CCR material for the purpose of beneficial use.

2) Notwithstanding subsection (b)(1), the owner or operator of the CCR surface impoundment may secure an additional two years to initiate closure of the idle surface impoundment if the Agency approves the owner's or operator's written demonstration that the CCR surface

impoundment will continue to accept wastes or will start removing CCR for the purpose of beneficial use. The documentation must be supported by, at a minimum, the information specified in this subsection (b)(2). The owner or operator may obtain two-year extensions, provided the owner or operator continues to be able to demonstrate that there is reasonable likelihood that the CCR surface impoundment will accept wastes in the foreseeable future or will remove CCR from the surface impoundment for the purpose of beneficial use. The owner or operator must place each Agency approved demonstration, if more than one time extension is sought, in the facility's operating record as required by Section 845.800(d)(21) before the end of any two-year period.

A) Information documenting that the CCR surface impoundment has remaining storage or disposal capacity or that the CCR surface impoundment can have CCR removed for the purpose of beneficial use; and

B) Information demonstrating that that there is a reasonable likelihood that the CCR surface impoundment will resume receiving CCR or non-CCR waste streams in the foreseeable future or that CCR can be removed for the purpose of beneficial use. The narrative must include a best estimate as to when the CCR surface impoundment will resume receiving CCR or non-CCR waste streams. The situations listed in this subsection (b)(2)(B) are examples of situations that would support a determination that the CCR surface impoundment will resume receiving CCR or non-CCR waste streams in the foreseeable future.

  i) Normal plant operations include periods during which the CCR surface impoundment does not receive CCR or non-CCR waste streams, such as the alternating use of two or more CCR surface impoundments whereby, at any point in time, one CCR surface impoundment is receiving CCR while CCR is being removed from a second CCR surface impoundment after its dewatering.

  ii) The CCR surface impoundment is dedicated to a coal-fired boiler surface impoundment that is temporarily idled (e.g., CCR is not being generated) and there is a reasonable likelihood that the coal-fired boiler will resume operations in the future.

  iii) The CCR surface impoundment is dedicated to an operating coal-fired boiler (i.e., CCR is being generated); however, no CCR is being placed in the CCR surface impoundment because the CCR is being entirely diverted to beneficial uses, but there is a reasonable likelihood that the CCR surface impoundment will again be used in the foreseeable future.

iv) The CCR surface impoundment currently receives only non-CCR waste streams and those non-CCR waste streams are not generated for an extended period of time, but there is a reasonable likelihood that the CCR surface impoundment will again receive non-CCR waste streams in the future.

3) In order to obtain additional time extensions to initiate closure of a CCR surface impoundment beyond the two years provided by subsection (b)(1), the owner or operator of the CCR surface impoundment must submit the demonstration required by subsection (b)(2) to the Agency for review and approval. The written documentation must include the following statement signed by the owner or operator or an authorized representative:

> I certify under penalty of law that I have personally examined and am familiar with the information submitted in this demonstration and all attached documents, and that, based on my inquiry of those individuals immediately responsible for obtaining the information, I believe that the submitted information is true, accurate, and complete. I am aware that there are significant penalties for submitting false information, including the possibility of fine and imprisonment.

c) The timeframes specified in subsections (a) and (b) do not apply to an owner or operator of a CCR surface impoundment closing the CCR surface impoundment as required by Section 845.700:

d) By the date the owner or operator initiates closure of a CCR surface impoundment, the owner or operator must prepare a notification of intent to close a CCR surface impoundment. The notification must be placed in the facility's operating record as required by Section 845.800(d)(21).

Section 845.740 Closure by Removal

a) Closure by Removal of CCR. An owner or operator may elect to close a CCR surface impoundment by removing all CCR and decontaminating all areas affected by releases of CCR from the CCR surface impoundment. CCR removal and decontamination of the CCR surface impoundment are complete when all CCR and CCR residues, containment system components such as the impoundment liner and contaminated subsoils, and CCR impoundment structures and ancillary equipment have been removed. Closure by removal must be completed before the completion of a groundwater corrective action under Subpart F.

b) After closure by removal has been completed, the owner or operator must continue groundwater monitoring under Subpart F for three years after the completion of closure or for three years after groundwater monitoring does not show an exceedance of the groundwater protection standard established under Section 845.600, whichever is longer.

c) The owner or operator of a CCR surface impoundment removing CCR during closure must responsibly handle and transport the CCR consistent with this subsection.

1) Transportation

A) Manifests

i) When transporting CCR off-site by motor vehicle, manifests must be carried as specified in 35 Ill. Adm. Code 809. For purposes of this Part, coal combustion fly ash that is removed from a CCR surface impoundment is not exempt from the manifest requirement.

ii) When transporting CCR off-site by any other mode or method, including trains or barges, manifests must be carried specifying, at a minimum, the following information: the volume of the CCR; the location from which the CCR was loaded onto the mode of transportation and the date the loading took place; and the location where the CCR is being taken and the date it will be delivered.

B) The owner or operator of a CCR surface impoundment from which CCR is removed and transported off-site must develop a CCR transportation plan, which must include:

i) Identification of the transportation method selected, including whether a combination of transportation methods will be used;

ii) The frequency, time of day, and routes of CCR transportation;

iii) Any measures to minimize noise, traffic, and safety concerns caused by the transportation of the CCR;

        iv) Measures to limit fugitive dust from any transportation of CCR;

        v) Installation and use of a vehicle washing station;

        vi) A means of covering the CCR for any mode of CCR transportation, including conveyor belts; and

        vii) A requirement that, for transport by motor vehicle, the CCR is transported by a permitted special waste hauler under 35 Ill. Adm. Code 809.201.

2) The owner or operator of a CCR surface impoundment must develop and implement onsite dust controls, which must include:

    A) A water spray or other commercial dust suppressant to suppress dust in CCR handling areas and haul roads; and

    B) Handling of CCR to minimize airborne particulates and offsite particulate movement during any weather event or condition.

3) The owner or operator of a CCR surface impoundment must provide the following public notices:

    A) Signage must be posted at the property entrance warning of the hazards of CCR dust inhalation; and

    B) When CCR is transported off-site, a written notice explaining the hazards of CCR dust inhalation, the transportation plan, and tentative transportation schedule must be provided to units of local government through which the CCR will be transported.

4) The owner or operator of the surface impoundment must take measures to prevent contamination of surface water, groundwater, soil and sediments from the removal of CCR, including the following:

    A) CCR removed from the surface impoundment may only be temporarily stored, and must be stored in a lined landfill, CCR surface impoundment, enclosed structure, or CCR storage pile.

    B) CCR storage piles must:

        i) Be tarped or constructed with wind barriers to suppress dust and to limit stormwater contact with storage piles;

ii) Be periodically wetted or have periodic application of dust suppressants;

iii) Have a storage pad, or a geomembrane liner, with a hydraulic conductivity no greater than 1 x 10^{-7} cm/sec, that is properly sloped to allow appropriate drainage;

iv) Be tarped over the edge of the storage pad where possible;

v) Be constructed with fixed and mobile berms, where appropriate, to reduce run-on and run-off of stormwater to and from the storage pile, and minimize stormwater-CCR contact; and

vi) Have a groundwater monitoring system that is consistent with the requirements of Section 845.630 and approved by the Agency.

C) The owner or operator of the CCR surface impoundment must incorporate general housekeeping procedures such as daily cleanup of CCR, tarping of trucks, maintaining the pad and equipment, and good practices during unloading and loading.

D) The owner or operator of the CCR must minimize the amount of time the CCR is exposed to precipitation and wind.

E) The discharge of stormwater runoff that has contact with CCR must be covered by an individual National Pollutant Discharge Elimination System (NPDES) permit. The owner or operator must develop and implement a Stormwater Pollution Prevention Plan (SWPPP) in addition to any other requirements of the facility's NPDES permit. Any construction permit application for closure must include a copy of the SWPPP.

d) At the end of each month during which CCR is being removed from a CCR surface impoundment, the owner or operator must prepare a report that:

1) Describes the weather, precipitation amounts, the amount of CCR removed from the CCR surface impoundment, the amount and location of CCR being stored on-site, the amount of CCR transported offsite, the implementation of good housekeeping procedures required by subsection (c)(4)(C), and the implementation of dust control measures; and

2) Documents worker safety measures implemented. The owner or operator of the CCR surface impoundment must place the monthly report in the facility's operating record as required by Section 845.800(d)(23).

e) Upon completion of CCR removal and decontamination of the CCR surface impoundment under subsection (a), the owner or operator of the CCR surface impoundment must submit to the Agency a completion of CCR removal and decontamination report and a certification from a qualified professional engineer that CCR removal and decontamination of the CCR surface impoundment has been completed in accordance with this Section. The owner or operator must place the CCR removal and decontamination report and certification in the facility's operating record as required by Section 845.800(d)(32).

f) Upon completion of groundwater monitoring required under subsection (b), the owner or operator of the CCR surface impoundment must submit to the Agency a completion of groundwater monitoring report and a certification from a qualified professional engineer that groundwater monitoring has been completed in accordance with this Section. The owner or operator must place the groundwater monitoring report and certification in the facility's operating record as required by Section 845.800(d)(24).

Section 845.750 Closure with a Final Cover System

Closure Performance Standard When Leaving CCR in Place:

a) The owner or operator of a CCR surface impoundment must ensure that, at a minimum, the CCR surface impoundment is closed in a manner that will:

  1) Control, minimize or eliminate, to the maximum extent feasible, post-closure infiltration of liquids into the waste and releases of CCR, leachate, or contaminated run-off to the ground or surface waters or to the atmosphere;

  2) Preclude the probability of future impoundment of water, sediment, or slurry;

  3) Include measures that provide for major slope stability to prevent the sloughing or movement of the final cover system during the closure and post-closure care period;

  4) Minimize the need for further maintenance of the CCR surface impoundment; and

  5) Be completed in the shortest amount of time consistent with recognized and generally accepted engineering practices.

b) Drainage and Stabilization of CCR Surface Impoundments. The owner or operator of a CCR surface impoundment or any lateral expansion of a CCR surface impoundment must meet the requirements of this subsection (b) before installing the final cover system required by subsection (c).

1) Free liquids must be eliminated by removing liquid wastes or solidifying the remaining wastes and waste residues.

2) Remaining wastes must be stabilized sufficiently to support the final cover system.

c) Final Cover System. If a CCR surface impoundment is closed by leaving CCR in place, the owner or operator must install a final cover system that is designed to minimize infiltration and erosion, and, at a minimum, meets the requirements of this subsection (c). The final cover system must consist of a low permeability layer and a final protective layer. The design of the final cover system must be included in the preliminary and final written closure plans required by Section 845.720 and the construction permit application for closure submitted to the Agency.

1) Standards for the Low Permeability Layer. The low permeability layer must have a permeability less than or equal to the permeability of any bottom liner system or natural subsoils present, or a hydraulic conductivity no greater than 1×10^{-7} cm/sec, whichever is less. The low permeability layer must be constructed in accordance with the standards in either subsection (c)(1)(A) or (c)(1)(B), unless the owner or operator demonstrates that another low permeability layer construction technique or material provides equivalent or superior performance to the requirements of either subsection (c)(1)(A) or (c)(1)(B) and is approved by the Agency.

A) A compacted earth layer constructed in accordance with the following standards:

i) The minimum allowable thickness must be 0.91 meter (three feet); and

ii) The layer must be compacted to achieve a hydraulic conductivity of 1×10^{-7} cm/sec or less and minimize void spaces.

B) A geomembrane constructed in accordance with the following standards:

i) The geosynthetic membrane must have a minimum thickness of 40 mil (0.04 inches) and, in terms of hydraulic flux, must be equivalent or superior to a three-foot layer of soil with a hydraulic conductivity of 1×10^{-7} cm/sec;

ii) The geomembrane must have strength to withstand the normal stresses imposed by the waste stabilization process; and

iii) The geomembrane must be placed over a prepared base free from sharp objects and other materials that may cause damage.

2) Standards for the Final Protective Layer. The final protective layer must meet the following requirements, unless the owner or operator demonstrates that another final protective layer construction technique or material provides equivalent or superior performance to the requirements of this subsection (c)(2) and is approved by the Agency.

A) Cover the entire low permeability layer;

B) Be at least three feet thick, be sufficient to protect the low permeability layer from freezing, and minimize root penetration of the low permeability layer;

C) Consist of soil material capable of supporting vegetation;

D) Be placed as soon as possible after placement of the low permeability layer; and

E) Be covered with vegetation to minimize wind and water erosion.

3) The disruption of the integrity of the final cover system must be minimized through a design that accommodates settling and subsidence.

4) The owner or operator of the CCR surface impoundment must obtain and submit with its construction permit application for closure a written certification from a qualified professional engineer that the design of the final cover system meets the requirements of this Section.

d) This subsection specifies the allowable uses of CCR in the closure of CCR surface impoundments closing under Section 845.700. Notwithstanding the prohibition on further placement in Section 845.700, CCR may be placed in these surface impoundments, but only for purposes of grading and contouring in the design and construction of the final cover system, if:

1) The CCR placed was generated at the facility and is located at the facility at the time closure was initiated;

2) CCR is placed entirely above the elevation of CCR in the surface impoundment, following dewatering and stabilization (see subsection (b));

3) The CCR is placed entirely within the perimeter berms of the CCR surface impoundment; and

4) The final cover system is constructed with either:

A) A slope not steeper than 5% grade after allowance for settlement; or

B) At a steeper grade, if the Agency determines that the steeper slope is necessary, based on conditions at the site, to facilitate run-off and minimize erosion, and that side slopes are evaluated for erosion potential based on a stability analysis to evaluate possible erosion potential. The stability analysis, at a minimum, must evaluate the site geology; characterize soil shear strength; construct a slope stability model; establish groundwater and seepage conditions, if any; select loading conditions; locate critical failure surface; and iterate until minimum factor of safety is achieved.

Section 845.760 Completion of Closure Activities

a) Except as provided for in subsection (b), the owner or operator must complete closure of existing and new CCR surface impoundments, and any lateral expansion of a CCR surface impoundment, within the timeframe approved by the Agency in the final closure plan, or within five years of obtaining a construction permit for closure, whichever is less.

b) Extensions of Closure Timeframes

1) The timeframes for completing closure of a CCR surface impoundment specified under subsection (a) may be extended if the owner or operator has demonstrated to the Agency that it was not feasible to complete closure of the CCR surface impoundment within the required timeframes due to factors beyond the facility's control.

2) The demonstration must include a narrative explaining the basis for additional time.

3) The owner or operator must submit the demonstration to the Agency with a renewal construction permit application for closure.

4) Factors that may support a demonstration include:

A) Complications stemming from the climate and weather, such as unusual amounts of precipitation or a significantly shortened construction season;

B) Time required to dewater a surface impoundment due to the volume of CCR contained in the CCR surface impoundment or the characteristics of the CCR in the surface impoundment;

C) Statement that the geology and terrain surrounding the CCR surface impoundment will affect the amount of material needed to close the CCR surface impoundment; or

D) Time required or delays caused by the need to coordinate with and obtain necessary approvals and permits from the Agency or other agencies.

c) Maximum Time Extensions

1) CCR surface impoundments of 40 acres or smaller that are not closing by removal may extend the time to complete closure by no longer than two years.

2) CCR surface impoundments larger than 40 acres that are not closing by removal may extend the timeframe to complete closure of the CCR surface impoundment multiple times, in two-year increments. For each two-year extension sought, the owner or operator must substantiate the factual circumstances demonstrating the need for the extension. No more than a total of five two-year extensions may be obtained for any CCR surface impoundment.

3) CCR surface impoundments that are closing by removal may extend the time to complete closure multiple times, in two-year increments. For each two-year extension sought, the owner or operator must substantiate the factual circumstances demonstrating the need for the extension. In no instance may the time allowed for closure by removal be extended beyond the completion of a groundwater corrective action as required by Section 845.680(c)(1).

d) In order to obtain an additional time extension to complete closure of a CCR surface impoundment beyond the times provided by subsection (a), the owner or operator of the CCR surface impoundment must include with the demonstration required by subsection (b) the following statement signed by the owner or operator or an authorized representative:

> I certify under penalty of law that I have personally examined and am familiar with the information submitted in this demonstration and all attached documents, and that, based on my inquiry of those individuals immediately responsible for obtaining the information, I believe that the submitted information is true, accurate, and complete. I am aware that

there are significant penalties for submitting false information, including the possibility of fine and imprisonment.

e) Upon completion of all closure activities required by this Part and approved in the final closure plan, the owner or operator of the CCR surface impoundment must submit to the Agency a closure report and a closure certification.

1) The closure report must contain supporting documentation, including:

A) Engineering and hydrogeology reports, including monitoring well completion reports and boring logs, all CQA reports, certifications, and designations of CQA officers-in-absentia required by Section 845.290;

B) Photographs, including time, date and location information of the photographs, of the final cover system and groundwater collection system, if applicable, and any other photographs relied upon to document construction activities;

C) A written summary of closure requirements and completed activities as stated in the closure plan and this Part; and

D) Any other information relied upon by the qualified professional engineer in making the closure certification.

2) The closure certification must include a statement from a qualified professional engineer that closure has been completed in accordance with the Agency-approved final closure plan and the requirements of this Section.

3) The owner or operator must place the closure report and certification in the facility's operating record as required by Section 845.800(d)(24).

f) Within 30 days after the Agency's approval of the closure report and closure certification submitted under subsection (e), the owner or operator must prepare a notification of closure of the CCR surface impoundment. The notification must include the certification by a qualified professional engineer required by subsection (e)(2). The owner or operator must place the notification in the facility's operating record as required by Section 845.800(d)(25).

g) If an owner or operator of a CCR surface impoundment has completed closure of the CCR surface impoundment before April 21, 2021, the owner or operator must notify the Agency of the completed closure by September 30, 2021, if that notification has not previously been submitted.

h) Deed Notations

1) Following closure of a CCR surface impoundment, the owner or operator must record a notation on the deed to the property, or some other instrument that is normally examined during title search.

2) The notation on the deed must in perpetuity notify any potential purchaser of the property that:

   A) The land has been used as a CCR surface impoundment; and

   B) Its use is restricted under the post-closure care requirements as provided by Section 845.780(d)(1)(C) or groundwater monitoring requirements in Section 845.740(b).

3) Within 30 days after recording a notation on the deed to the property, the owner or operator must submit to the Agency a notification stating that the notation has been recorded. The owner or operator must place the notification in the facility's operating record as required by 845.800(d)(26).

Section 845.770 Retrofitting

Retrofit of a CCR surface impoundment must be completed in accordance with the requirements of this Section.

a) To retrofit an existing CCR surface impoundment, the owner or operator must:

   1) First remove all CCR, including any liners except as specified in subsection (a)(4), as necessary, and contaminated soils and sediments from the CCR surface impoundment;

   2) Comply with the requirements in Sections 845.410 and 845.420; and

   3) Within 30 days after April 21, 2021, the owner or operator electing to retrofit a CCR surface impoundment under this Section must submit a written preliminary retrofit plan to the Agency and post the written preliminary retrofit plan in the facility's operating record as required by Section 845.800(d)(27). The written preliminary retrofit plan must include a prioritization categorization under Section 845.700(g) and the expected construction permit application date under Section 845.700(h); and

   4) An owner or operator may request the Agency to approve the use of an existing competent geomembrane liner as a supplemental liner by submitting visual inspection, and analytical testing results to demonstrate that the existing liner is not contaminated with CCR constituents.

b) A CCR surface impoundment undergoing a retrofit remains subject to all other requirements of this Part, including the requirement to conduct any necessary corrective action.

c) Written Retrofit Plan

1) Content of the Plan. The owner or operator must prepare a written retrofit plan that describes the steps necessary to retrofit the CCR surface impoundment consistent with recognized and generally accepted engineering practices. The written retrofit plan must include, at a minimum, all the following information:

A) A narrative description of the specific measures that will be taken to retrofit the CCR surface impoundment in accordance with this Section.

B) A description of the procedures to remove all CCR, liners as necessary, and contaminated soils and sediments from the CCR surface impoundment.

C) An estimate of the maximum amount of CCR and other contaminated materials that will be removed as part of the retrofit operation.

D) An estimate of the largest area of the CCR surface impoundment that will be affected by the retrofit operation.

E) A schedule for completing all activities necessary to satisfy the retrofit criteria in this Section, including an estimate of the year in which retrofit activities of the CCR surface impoundment will be completed.

2) The owner or operator must submit the written retrofit plan with the construction permit application and must obtain a construction permit before retrofitting a CCR surface impoundment.

3) Amendment of a Written Retrofit Plan.

A) The owner or operator may submit a permit modification application to amend the initial or any subsequent written retrofit plan at any time.

B) The owner or operator must seek to amend the written retrofit plan whenever:

i) There is a change in the operation of the CCR surface impoundment that would substantially affect the written retrofit plan in effect; or

ii) unanticipated events necessitate a revision of the written retrofit plan either before or after retrofit activities have started.

C) The owner or operator must seek to amend the retrofit plan at least 60 days before a planned change in the operation of the facility or CCR surface impoundment, or within 60 days after an unanticipated event requires the revision of an existing written retrofit plan. If a written retrofit plan needs to be revised after retrofit activities have started for a CCR surface impoundment, the owner or operator must submit a request to modify the construction permit within 60 days following the triggering event.

4) The owner or operator of the CCR surface impoundment must obtain a written certification from a qualified professional engineer that the activities outlined in the written retrofit plan, including any amendment of the plan, meet the requirements of this Section.

d) By the date the owner or operator submits a construction permit application to the Agency to retrofit a CCR surface impoundment, the owner or operator must prepare a notification of intent to retrofit a CCR surface impoundment. The owner or operator has completed the notification when it has been placed in the facility's operating record as required by Section 845.800(d)(28).

e) When activities related to retrofitting the CCR surface impoundment include the removal of CCR from the surface impoundment, the handling and removal of CCR must be performed in a manner consistent with the requirements of Section 845.740.

f) Deadline for Completion of Activities Related to the Retrofit of a CCR Surface Impoundment. Any CCR surface impoundment that is being retrofitted must complete all retrofit activities within the timeframe approved by the Agency in the retrofit plan, or within five years after obtaining a construction permit, whichever is less. The same procedures specified for the extension closure timeframes in Section 845.760(b) apply to extension of retrofit timeframes.

g) Upon completion of all retrofit activities required by this Part and approved by the Agency in a construction permit, the owner or operator of the CCR surface impoundment must submit to the Agency a retrofit completion report and certification.

1) The retrofit completion report must contain supporting documentation, including:

   A) Engineering and hydrogeology reports, including monitoring well completion reports and boring logs, all CQA reports, certifications, and designations of CQA officers-in-absentia required by Section 845.290;

   B) Photographs, including time, date and location information of the photographs, of the liner system and leachate collection system, and any other photographs relied upon to document construction activities;

   C) A written summary of retrofit requirements and completed activities as stated in the construction permit and this Part; and

   D) Any other information relied upon by the qualified professional engineer in making the closure certification.

2) The retrofit certification must include a statement from a qualified professional engineer that retrofit has been completed in accordance with the retrofit plan specified in subsection (c) and the requirements of this Part.

3) The owner or operator must place the retrofit completion report and certification in the facility's operating record as required by Section 845.800(d)(29).

h) Within 30 days after the Agency's approval of the retrofit completion report and certification submitted under subsection (g), the owner or operator must prepare a notification of completion of retrofit activities. The notification must include the certification by a qualified professional engineer as required by subsection (g)(2). The owner or operator has completed the notification when it has been placed in the facility's operating record as required by Section 845.800(d)(30).

i) At any time after the initiation of a CCR surface impoundment retrofit, the owner or operator may stop the retrofit and seek to initiate closure of the CCR surface impoundment in accordance with the requirements of this Subpart G. The owner or operator of the CCR surface impoundment must obtain an approved construction permit for closure.

Section 845.780 Post-Closure Care Requirements

a) Applicability

1) Except as provided by subsection (a)(2), this Section applies to the owners or operators of CCR surface impoundments who have completed an Agency approved closure.

2) An owner or operator of a CCR surface impoundment that elects to close a CCR surface impoundment by removing CCR as provided by Section 845.740 is not subject to the post-closure care criteria of this Section.

b) Post-closure Care Maintenance Requirements. Following closure of the CCR surface impoundment, the owner or operator must conduct post-closure care for the CCR surface impoundment, which must consist of at least the following:

1) Maintaining the integrity and effectiveness of the final cover system, including making repairs to the final cover as necessary to correct the effects of settlement, subsidence, erosion, or other events, and preventing run-on and run-off from eroding or otherwise damaging the final cover;

2) If the CCR surface impoundment is subject to the design criteria of Section 845.420, maintaining the integrity and effectiveness of the leachate collection and removal system and operating the leachate collection and removal system in accordance with the requirements of Section 845.420; and

3) Maintaining the groundwater monitoring system and monitoring the groundwater in accordance with the requirements of Subpart F.

c) Post-closure Care Period

1) Except as provided by subsection (c)(2), the owner or operator of the CCR surface impoundment must conduct post-closure care for 30 years.

2) At the end of the 30-year post-closure care period, the owner or operator of the CCR surface impoundment must continue to conduct post-closure care until the groundwater monitoring data shows the concentrations are:

A) Below the groundwater protection standards in Section 845.600; and

B) Not increasing for those constituents over background, using the statistical procedures and performance standards in Section 845.640(f) and (g), provided that:

i) Concentrations have been reduced to the maximum extent feasible; and

ii) Concentrations are protective of human health and the environment.

d) Written Post-closure Care Plan

1) Content of the Plan. The owner or operator of a CCR surface impoundment must prepare a written post-closure care plan that includes, at a minimum, the information specified in this subsection (d)(1).

A) A description of the monitoring and maintenance activities required in subsection (b) for the CCR surface impoundment and the frequency at which these activities will be performed;

B) The name, address, telephone number, and email address of the person or office to contact about the facility during the post-closure care period; and

C) A description of the planned uses of the property during the post-closure care period. Post-closure use of the property must not disturb the integrity of the final cover, liners, or any other component of the containment system, or the function of the monitoring systems unless necessary to comply with the requirements of this Part. Any other disturbance is allowed if the owner or operator of the CCR surface impoundment demonstrates that disturbance of the final cover, liner, or other component of the containment system, including any removal of CCR, will not increase the potential threat to human health or the environment. The demonstration must be certified by a qualified professional engineer and must be submitted to the Agency.

2) Deadline to Prepare the Initial Written Post-closure Care Plan. The owner or operator of a CCR surface impoundment must submit to the Agency an initial written post-closure care plan consistent with the requirements specified in subsection (d)(1), with its initial operating permit application.

3) Amendment of a Written Post-closure Care Plan.

A) The owner or operator may submit an operating permit modification application to amend the initial or any subsequent written post-closure care plan developed under subsection (d)(1) at any time.

B) The owner or operator must seek to amend the written closure care plan whenever:

i) There is a change in the operation of the CCR surface impoundment that would substantially affect the written post-closure care plan in effect; or

ii) unanticipated events necessitate a revision of the written post-closure care plan, after post-closure activities have started.

C) The owner or operator must seek to amend the written post-closure care plan at least 60 days before a planned change in the operation of the facility or CCR surface impoundment, or within 60 days after an unanticipated event requires the need to revise an existing written post-closure care plan. If a written post-closure care plan is revised after post-closure activities have started for a CCR surface impoundment, the owner or operator must submit a request to modify the operating permit within 30 days following the triggering event.

4) The owner or operator of the CCR surface impoundment must obtain a written certification from a qualified professional engineer that the initial, and any amendment of the, written post-closure care plan meets the requirements of this Section.

e) Upon the completion of the post-closure care period, the owner or operator of the CCR surface impoundment must submit a request to the Agency to terminate post-closure care. The request must include a certification by a qualified professional engineer verifying that post-closure care has been completed in accordance with the post-closure care plan specified in subsection (d) and the requirements of this Section.

f) Notification of Completion of Post-closure Care Period. Within 30 days after the Agency's approval of the owner's or operator's request to terminate post-closure care, the owner or operator must prepare a notification of completion of post-closure care and must place the notification in the facility's operating record as required by Section 845.800(d)(31).

SUBPART H: RECORDKEEPING

Section 845.800 Facility Operating Record

a) Each owner or operator of a CCR surface impoundment subject to the requirements of this Part must maintain files of all information required by this Section in a written operating record at the facility.

b) Unless specified otherwise, each file must be retained for at least three years past the date the Agency approved the owner's or operator's request to terminate post-closure care, when closure is with a final cover system, or the completion of groundwater monitoring under Section 845.740(b), when closure is by removal.

c) An owner or operator of more than one CCR surface impoundment subject to the provisions of this Part may comply with the requirements of this Section in one recordkeeping system provided the system identifies each file by the name and identification number of each CCR surface impoundment. The files may be maintained on microfilm, on a computer, on computer disks, on a storage system accessible by a computer, on magnetic tape disks, or on microfiche.

d) Unless otherwise required below, the owner or operator of a CCR surface impoundment must place the following information, as it becomes available, in the facility's operating record:

1) Copies of all permit applications and permits issued under this Part;

2) Documentation recording the public meetings held under Section 845.240;

3) Weekly CQA reports under Section 845.290(b);

4) Hazard potential classification assessments for CCR surface impoundments (see Section 845.440(a)(3)(D));

5) Structural stability assessments for CCR surface impoundments (see Section 845.450(d)(4));

6) Safety factor assessments for CCR surface impoundments (see Section 845.460(c)(4));

7) The CCR fugitive dust control plan and any subsequent amendment of the plan (see Section 845.500(b)(6)), except that only the most recent fugitive dust control plan must be maintained in the facility's operating record, irrespective of the time requirement specified in subsection (b);

8) Inflow design flood control system plans for CCR surface impoundments (see Section 845.510(c)(4)(D));

9) Emergency Action Plan (see Section 845.520(a)), except that only the most recent EAP must be maintained in the facility's operating record irrespective of the time requirement specified in subsection (b);

10) Documentation prepared by the owner or operator recording all activations of the EAP (see Section 845.520(f));

11) Documentation prepared by the owner or operator recording the annual face-to-face meeting or exercise between representatives of the owner or

operator of the CCR surface impoundment and the local emergency responders (see Section 845.520(g));

12) Safety and Health Plan (see Section 845.530(a));

13) Documentation recording the results of each inspection and instrumentation monitoring by a qualified person (see Section 845.540(a)(2));

14) Annual consolidated report (see Section 845.550), which contains the following:

    A) The annual CCR fugitive dust control report (see Section 845.500(c));

    B) The annual inspection report (see Section 845.540(b)(3)); and

    C) The annual groundwater monitoring and corrective action report (see Section 845.610(e));

15) All groundwater monitoring data submitted to the Agency and any analysis performed (see Section 845.610(b)(3)(D));

16) Within 30 days after detecting one or more monitored constituents above the groundwater protection standard, the notifications required by Section 845.650(d) and (e);

17) The semi-annual report describing the progress in selecting and designing the remedy (see Section 845.670(a));

18) Within 30 days after completing the corrective action plan, the notification required by Section 845.680(e);

19) USEPA-approved or denied demonstration as required by Section 845.700(d)(2)(F);

20) The preliminary written closure plan and any amendment of the plan (see Section 845.720(a)) except that only the most recent closure plan must be maintained in the facility's operating record, irrespective of the time requirement specified in subsection (b);

21) The written demonstrations, including the certification required by Section 845.730(b)(3), for a time extension for initiating closure (see Section 845.730(b)(2));

22) The notification of intent to close a CCR surface impoundment (see Section 845.730(d));

23) The monthly reports for closure by removal (see Section 845.740(d));

24) The closure report and certification (see Section 845.760(e)(3)), or the completion of groundwater monitoring report and certification (see Section 845.740(f));

25) The notification of completion of closure of a CCR surface impoundment (see Section 845.760(f));

26) The notification recording a notation on the deed (see Section 845.760(h));

27) The preliminary written retrofit plan for a CCR surface impoundment (see Section 845.770(a)(3));

28) The notification of intent to initiate retrofit of a CCR surface impoundment (see Section 845.770(d));

29) The retrofit completion report and certification (see Section 845.770(g)(3));

30) The notification of completion of retrofit activities (see Section 845.770(h));

31) The notification of completion of post-closure care period (see Section 845.780(f));

32) The completion of CCR removal and decontamination report and certification (see Section 845.740(e)); and

33) The most current cost estimates (see Section 845.940(d)).

Section 845.810 Publicly Accessible Internet Site Requirements

a) Each owner or operator of a CCR surface impoundment subject to the requirements of this Part must maintain a publicly accessible Internet site (CCR website) containing the information specified in this Section. The owner's or operator's website must be titled "Illinois CCR Rule Compliance Data and Information".

b) An owner or operator of more than one CCR surface impoundment subject to the provisions of this Part may comply with the requirements of this Section by using the same Internet site for multiple CCR surface impoundments, provided the CCR website clearly delineates information by the name and identification number of each CCR surface impoundment.

c) Unless otherwise required in this Section, the information required to be posted to the CCR website must be made available to the public on the CCR website until 3 years after post-closure care (when closure is with a final cover system) or the completion of groundwater monitoring under Section 845.740(b) (when closure is by removal).

d) Unless otherwise required in this Section, the information must be posted to the CCR website within 14 days after placing the pertinent information required by Section 845.800 in the operating record.

e) The owner or operator must place all the information specified under Section 845.800(d) on the owner's or operator's CCR website.

f) The owner or operator must place all the information specified in Section 845.240(e) on the owner's or operator's CCR website at least 30 days before the public meeting.

g) The owner or operator must notify the Agency of the web address of the publicly accessible Internet site, including any change to the web address. The Agency must maintain a list of these web addresses on the Agency's website.

SUBPART I: FINANCIAL ASSURANCE

Section 845.900 General Provisions

a) This Subpart provides procedures by which the owner or operator of a CCR surface impoundment subject to this Part provides financial assurance satisfying the requirements of Section 22.59(f) of the Act.

b) The owner or operator must provide financial assurance to ensure the following:

  1) Completion of closure;

  2) Completion of post-closure care, if applicable; and

  3) Remediation of releases from a CCR surface impoundment.

c) The owner or operator must maintain financial assurance equal to or greater than the current cost estimates always calculated under Section 845.930, except as otherwise provided by Section 845.910.

d) Financial assurance must be provided, by a trust agreement, a surety bond guaranteeing payment, a surety bond guaranteeing payment or performance, or an irrevocable letter of credit (see Section 845.950). The owner or operator must provide financial assurance to the Agency within the timeframes in Section 845.950(c).

e) This Subpart does not apply to the State of Illinois, its agencies and institutions, any unit of local government, or any not-for-profit electric cooperative as defined in Section 3.4 of the Electric Supplier Act [220 ILCS 30].

f) The Agency is authorized to enter into contracts and agreements necessary to carry out the purposes of this Subpart and of Section 22.59(f) of the Act. Neither the State, nor the Director of the Agency, nor any State employee will be liable for any damages or injuries arising out of, or resulting from, any action taken under this Part.

g) The Agency may sue in any court of competent jurisdiction to enforce its rights under financial instruments. The filing of an enforcement action before the Board is not a condition precedent to such an Agency action, except when this Subpart or the terms of the instrument provide otherwise.

h) The Agency must have the authority to approve or disapprove any financial assurance mechanism posted or submitted under this Subpart.

i) The following Agency actions may be appealed to the Board as a permit denial under Section 845.270(e) and Section 22.59(f)(3) of the Act:

  1) A refusal to accept financial assurance tendered by the owner or operator;

  2) A refusal to release the owner or operator from the requirement to maintain financial assurance;

  3) A refusal to release excess funds from a trust;

  4) A refusal to approve a reduction in the penal sum of a bond; and

  5) A refusal to approve a reduction in the amount of a letter of credit.

j) An owner or operator must notify the Agency by certified mail of the beginning of a voluntary or involuntary proceeding under Title 11 of the United States Code (Bankruptcy) naming any of the owners or operators as debtor, within 10 days after the proceeding starts.

k) An owner or operator that fulfills the requirements of Section 845.960, 845.970, 845.980, or 845.990 by obtaining a trust fund, surety bond, or letter of credit will be deemed to be without the required financial assurance in the event of bankruptcy of the trustee or issuing institution, or a suspension or revocation of the authority of the trustee institution to act as trustee or of the institution issuing the surety bond or letter of credit to issue those instruments. The owner or operator must establish alternative financial assurance within 60 days after such an event.

Section 845.910 Upgrading Financial Assurance

a) The owner or operator must increase the total amount of financial assurance to equal or exceed the current cost estimate within 60 days after either of the following occurrences:

1) An increase in the current cost estimate; or

2) A decrease in the value of a trust fund.

b) The owner or operator of a CCR surface impoundment must make annual adjustments for inflation if required under Section 845.930 or 845.940.

Section 845.920 Release of Financial Institution and Owner or Operator

a) The Agency must release a trustee, surety, or other financial institution when:

1) An owner or operator substitutes alternative financial assurance such that the total financial assurance for the CCR surface impoundment is equal to or greater than the current cost estimate, without counting the amounts to be released; or

2) The Agency releases the owner or operator from the requirements of this Subpart under subsection (b).

b) The Agency must release an owner or operator of a CCR surface impoundment from the requirements of this Subpart under the following circumstances:

1) Completed Closure. In the Agency's approval of the closure report and certification under Section 845.760, the Agency must notify the owner or operator in writing that it is no longer required by this Subpart to maintain financial assurance for closure of the CCR surface impoundment.

2) Completed Post-Closure Care. In the Agency's approval of the owner's or operator's request to terminate post-closure care under Section 845.780, the Agency must notify the owner or operator in writing that it is no longer required by this Subpart to maintain financial assurance for post-closure care of the CCR surface impoundment.

3) Completed Corrective Action. In the Agency's approval of the corrective action completion report and certification under Section 845.680, the Agency must notify the owner or operator in writing that it is no longer

required by this Subpart to maintain financial assurance for corrective action.

Section 845.930 Cost Estimates

a) The owner or operator must prepare and submit to the Agency, for approval, written cost estimates for:

1) The total costs for closure and post-closure care;

2) Preliminary corrective action costs; and

3) The total costs of the corrective action plan for remediation of any releases from a CCR surface impoundment.

b) Written Cost Estimate for Closure and Post-closure

1) The owner or operator must have a detailed written estimate, in current dollars, of the cost of closing the CCR surface impoundment in accordance with this Part and providing post-closure care on an annual basis, when required, in accordance with this Part. The cost estimate is the total cost for closure and post-closure care.

2) The cost estimate must equal the cost of final closure and post-closure care at the point in the CCR surface impoundment's active life when the extent and manner of its operation would make closure and post-closure care the most expensive.

3) The cost estimate must be based on the assumption that the Agency will contract with a third party at the appropriate prevailing wages, under the Prevailing Wage Act [820 ILCS 130], if applicable, to implement the closure and post-closure care plans. A third party is a party who is neither a parent nor a subsidiary of the owner or operator.

4) The cost estimate may not be reduced by allowance for the salvage value of facility structures or equipment, for the resale value of land, for the sale of CCR or its beneficial reuse if permitted by the Agency under this Part, or for other assets associated with the facility at the time of partial or final closure.

5) The owner or operator must not incorporate a zero cost for CCR, if permitted by the Agency under this Part, that might have economic value.

6) The cost estimate must, at a minimum, include all costs for all activities necessary to close the CCR surface impoundment and provide post-closure care in accordance with all requirements.

7) The post-closure care portion of the cost estimate must, at a minimum, be based on the following elements:

A) Maintaining the integrity and effectiveness of the final cover system, including making repairs to the final cover as necessary to correct the effects of settlement, subsidence, erosion, or other events, and preventing run-on and run-off from eroding or otherwise damaging the final cover;

B) If the CCR surface impoundment is subject to the design criteria of Section 845.420, maintaining the integrity and effectiveness of the leachate collection and removal system and operating the leachate collection and removal system in accordance with the requirements of Section 845.420; and

C) Maintaining the groundwater monitoring system and monitoring the groundwater in accordance with the requirements of this Part.

c) Cost Estimate for Corrective Action

1) Preliminary Corrective Action Cost Estimate. An owner or operator of a CCR surface impoundment with a release that has caused an exceedance of the groundwater protection standard in Section 845.600, or groundwater quality standard in 35 Ill. Adm. Code 620, must provide a preliminary corrective action cost estimate that is equal to 25% of the costs calculated under subsection (b).

2) Corrective Action Cost Estimate. The owner or operator must provide to the Agency a detailed written estimate, in current dollars, of the cost of hiring a third party at the appropriate prevailing wages, under the Prevailing Wage Act, if applicable, to implement the approved corrective action plan in accordance with this Part. The corrective action cost estimate must account for the total costs of corrective action activities as described in the approved corrective action plan for the entire corrective action period.

3) The owner or operator must annually adjust the cost estimates in this subsection (c) for inflation (see Section 845.940(a)) until the approved corrective action plan is completed.

4) The owner or operator must increase the corrective action cost estimates in this subsection (c) and the amount of financial assurance provided if changes in the corrective action plan or CCR surface impoundment conditions increase the maximum costs of corrective action.

5) The owner or operator may reduce the amount of the corrective action cost estimate, upon Agency approval, if the cost estimate exceeds the maximum remaining costs of corrective action.

Section 845.940 Revision of Cost Estimates

a) During the active life of the CCR surface impoundment, the owner or operator must adjust the cost estimates for closure, post-closure care, and corrective action for inflation on an annual basis. The adjustments must occur within 60 days before the anniversary date of the establishment of the financial instruments used to comply with Section 845.950. The adjustment may be made by recalculating the maximum costs of closure, post-closure care, or corrective action in current dollars, or by using an inflation factor derived from the annual Implicit Price Deflator for Gross National Product (Deflator) as published by the U.S. Department of Commerce in its Survey of Current Business (Table 1.1.9) (see subsections (a)(1) and (a)(2)). The inflation factor is the result of dividing the latest published annual Deflator by the Deflator for the previous year.

1) The first adjustment is made by multiplying the cost estimate by the inflation factor. The result is the adjusted cost estimate.

2) Subsequent adjustments are made by multiplying the latest adjusted cost estimate by the latest inflation factor.

b) During the active life of the CCR surface impoundment, the owner or operator must revise the cost estimate within 30 days after the Agency has approved a request to modify the corrective action plan, closure plan, or post-closure care plan, if the change in the modified plan increases the cost of corrective action, closure or post-closure care. The revised cost estimate must be adjusted for inflation (see subsection (a)).

c) At least 60 days before submitting any closure plan to the Agency, the owner or operator must revise the cost estimate if the selected closure method increases the estimated closure or post-closure care costs.

d) The owner or operator must keep the most current cost estimates in the facility's operating record during the operating life of the CCR surface impoundment.

Section 845.950 Mechanisms for Financial Assurance

a) The owner or operator of a CCR surface impoundment must use any of the mechanisms listed in this subsection (a) to provide financial assurance for closure and post-closure care, and for corrective action at a CCR surface impoundment. An owner or operator of a CCR surface impoundment must also meet the requirements of subsections (b), (c), and (d). The mechanisms are as follows:

1) A trust fund (see Section 845.960);

2) A surety bond guaranteeing payment (see Section 845.970);

3) A surety bond guaranteeing performance (see Section 845.980); or

4) An irrevocable letter of credit (see Section 845.990).

b) The owner or operator of a CCR surface impoundment must ensure that the language of the mechanisms listed in subsection (a), when used for providing financial assurance for closure, post-closure, and corrective action, is consistent with the forms prescribed by the Agency and satisfies the following:

1) The amount of funds assured is sufficient to cover the costs of closure, post-closure care, and corrective action; and

2) The funds will be available in a timely fashion when needed.

c) The owner or operator of a CCR surface impoundment must provide financial assurance utilizing one or more of the mechanisms listed in subsection (a) within the following timeframes:

1) An owner or operator of an existing CCR surface impoundment must provide financial assurance to the Agency for closure and post-closure care within 60 days after April 21, 2021;

2) An owner or operator of a new CCR surface impoundment must provide financial assurance to the Agency for closure and post-closure care at least 60 days before the date of initial receipt of CCR in the CCR surface impoundment.

3) In the case of corrective action required by this Part, the owner or operator of the CCR surface impoundment must provide preliminary financial assurance for corrective action no later than when the owner or operator initiates an assessment of corrective measures under Section 845.650(d)(3). The preliminary financial assurance for corrective action must be maintained until replaced with financial assurance based on the cost estimate of the corrective action. The owner or operator of the CCR surface impoundment must provide financial assurance based on the approved corrective action plan to the Agency within 60 days after either the Agency's approval or April 21, 2021, whichever is later.

d) The owner or operator must provide continuous financial assurance coverage until the owner or operator is released from the financial assurance requirements of this Subpart under Section 845.920(b).

e) Use of Multiple Financial Assurance Mechanisms. An owner or operator may satisfy the requirements of this Subpart by establishing more than one financial mechanism per CCR surface impoundment. These mechanisms are limited to trust funds, surety bonds guaranteeing payment, and letters of credit. The mechanisms must be as specified in Sections 845.960, 845.970, and 845.990, as applicable, except that it is the combination of mechanisms, rather than the single mechanism, that must provide financial assurance for an aggregate amount at least equal to the current cost estimate for closure, post-closure care, and corrective action, except that mechanisms guaranteeing performance, rather than payment, may not be combined with other instruments. The owner or operator may use any or all the mechanisms to provide financial assurance for corrective action, closure and post-closure care.

f) Use of a Financial Assurance Mechanism for Multiple CCR Surface Impoundments in Illinois. An owner or operator may use a financial assurance mechanism specified in this Subpart to meet the requirements of this Subpart for more than one CCR surface impoundment located in Illinois. Evidence of financial assurance submitted to the Agency must include a list showing, for each CCR surface impoundment, the identification number (see Section 845.130), name, address and the amount of funds assured by the mechanism. The amount of funds available through the mechanism must be at least the sum of funds that would be available if a separate mechanism had been established and maintained for each CCR surface impoundment. The amount of funds available to the Agency must be enough to close and provide post-closure care for all of the owner's or operator's CCR surface impoundments. In directing funds available through a single mechanism for the closure and post-closure care of any single CCR surface impoundment covered by that mechanism, the Agency must direct only that amount of funds designated for that CCR surface impoundment, unless the owner or operator agrees to the use of additional funds available under that mechanism.

Section 845.960 Trust Fund

a) An owner or operator may satisfy the requirements of this Subpart by establishing a fully funded trust fund that conforms to the requirements of this Section and submitting to the Agency an original signed duplicate of the trust agreement.

b) The trustee must be an entity that has the authority to act as a trustee and of whom either of the following is true:

1) It is an entity whose trust operations are examined by the Illinois Department of Financial and Professional Regulation under the Illinois Banking Act [205 ILCS 5]; or

2) It is an entity that complies with the Corporate Fiduciary Act [205 ILCS 620].

c) The trust agreement must be on forms prescribed by the Agency. The trust agreement must be updated within 60 days after a change in the amount of the current closure, post-closure, and corrective action cost estimates covered by the agreement.

d) The trust fund must be fully funded from the date that the trust agreement becomes effective.

e) The trustee must evaluate the trust fund annually, as of the day the trust was created or on such earlier date as may be provided in the agreement. The trustee must notify the owner or operator and the Agency of the value within 30 days after the evaluation date.

f) If the owner or operator of a CCR surface impoundment establishes a trust fund after having used one or more alternative mechanisms specified in this Subpart, the trust fund must be fully funded and established according to the specifications of this Section.

g) Release of Excess Funds

  1) If the value of the financial assurance is greater than the total amount of the current cost estimate, the owner or operator may submit a written request to the Agency for a release of the amount in excess of the current cost estimate.

  2) Within 60 days after receiving a request from the owner or operator for a release of funds, the Agency must instruct the trustee to release to the owner or operator the funds as the Agency specifies in writing to be in excess of the current cost estimate.

h) Reimbursement for Closure, Post-closure Care, and Corrective Action Expenses

  1) After initiating corrective action, closure, or post-closure care an owner or operator, or any other person authorized to perform corrective action, closure, or post-closure care, may request reimbursement for closure, post-closure care, or corrective action expenditures by submitting itemized bills to the Agency.

  2) Within 60 days after receiving the itemized bills for closure, post-closure care, or correction action activities, the Agency must determine whether the expenditures are in accordance with the closure, post-closure care, or corrective action plan. The Agency must instruct the trustee to make reimbursement in amounts the Agency specifies in writing as expenditures made in accordance with the closure, post-closure care, or corrective action plan.

3) If the Agency determines, based on information available to it, that the cost of closure and post-closure care or corrective action will be greater than the value of the trust fund, it must withhold reimbursement of amounts it determines are necessary to preserve the fund in order to accomplish closure and post-closure care or corrective action until it determines that the owner or operator is no longer required to maintain financial assurance for closure and post-closure care or corrective action. If the fund is inadequate to pay all claims, the Agency must pay claims according to the following priorities:

A) Persons with whom the Agency has contracted to perform closure, post-closure care, or corrective action activities (first priority);

B) Persons who have completed closure, post-closure care, or corrective action authorized by the Agency (second priority);

C) Persons who have completed work that furthered the closure, post-closure care, or corrective action (third priority);

D) The owner or operator and related business entities (last priority).

Section 845.970 Surety Bond Guaranteeing Payment

a) An owner or operator may satisfy the requirements of this Subpart by obtaining a surety bond that conforms to the requirements of this Section and submitting the bond to the Agency.

b) The surety company issuing the bond must, at a minimum, be among those listed as acceptable sureties on federal bonds in Circular 570 of the U.S. Department of the Treasury. Circular 570 is available on the Internet from the following website: https://fiscal.treasury.gov/surety-bonds/circular-570.html.

c) The surety bond must be on forms prescribed by the Agency.

d) Any payments drawn from or made under the bond will be placed in the Coal Combustion Residual Surface Impoundment Financial Assurance Fund within the State Treasury.

e) Conditions

1) The bond must guarantee that the owner or operator will:

A) Provide closure and post-closure care in accordance with the approved closure and post-closure care plans and, if the bond is a corrective action bond, provide corrective action in accordance with this Part; and

B) Provide alternative financial assurance, as specified in this Subpart, and obtain the Agency's written approval of the assurance provided within 90 days after receipt by both the owner or operator and the Agency of a notice from the surety that the bond will not be renewed for another term.

2) The surety will become liable on the bond obligation when, during the term of the bond, the owner or operator fails to perform as guaranteed by the bond. The owner or operator fails to perform when the owner or operator:

A) Abandons the CCR surface impoundment;

B) Is adjudicated bankrupt;

C) Fails to initiate closure of the CCR surface impoundment or post-closure care or corrective action when ordered to do so by the Board under Title VIII of the Act (Enforcement), or when ordered to do so by a court of competent jurisdiction;

D) Notifies the Agency that it has initiated closure or corrective action, or initiates closure or corrective action, but fails to close the CCR surface impoundment or provide post-closure care or corrective action in accordance with the Agency-approved closure and post-closure care or corrective action plans;

E) For a corrective action bond, fails to implement or complete corrective action at a CCR surface impoundment in accordance with Section 845.670; or

F) Fails to, within 90 days after receipt by both the owner or operator and the Agency of a notice from the surety that the bond will not be renewed for another term:

i) Provide alternative financial assurance, as specified in this Subpart; and

ii) Obtain the Agency's written approval of the assurance.

3) If the owner or operator does not establish alternative financial assurance, as specified in this Subpart, and obtain written approval of that alternative assurance from the Agency within 90 days after receipt by both the owner or operator and the Agency of a notice of nonrenewal from the surety (see subsection (g)(2)), the Agency must draw on the bond. During the last 30

days of a notice of nonrenewal, the Agency must draw on the bond if the owner or operator has failed to provide alternative financial assurance, as specified in this Section, and obtain from the Agency written approval of that assurance.

f) Penal Sum

1) The penal sum of the bond must be in an amount at least equal to the current cost estimate.

2) Whenever the current cost estimate decreases, the penal sum may be reduced to the amount of the current cost estimate following written approval by the Agency.

3) Whenever the current cost estimate increases to an amount greater than the penal sum, the owner or operator, within 90 days after the increase, must either cause the penal sum to be increased to an amount at least equal to the current cost estimate and submit evidence of that increase to the Agency or obtain other financial assurance, as specified in this Subpart, to cover the increase and submit evidence of the alternative financial assurance to the Agency.

g) Term

1) The bond must be issued for a term of at least one year and must not be cancelable during that term.

2) The surety bond must provide that, on the current expiration date and on each successive expiration date, the term of the surety bond will be automatically extended for a period of at least one year unless, at least 120 days before the current expiration date, the surety notifies both the owner or operator and the Agency by certified mail of a decision not to renew the bond. Under the terms of the surety bond, the 120 days will begin on the date when both the owner or operator and the Agency have received the notice, as evidenced by the return receipts.

3) The Agency must release the surety by providing written authorization for termination of the bond to the owner or operator and the surety when either of the following occurs:

A) An owner or operator substitutes alternative financial assurance, as specified in this Subpart; or

B) The Agency releases the owner or operator from the requirements of this Subpart in accordance with Section 845.920(b).

h) Cure of Default and Refunds

1) The Agency must release the surety if, after the surety becomes liable on the bond, the owner or operator or another person provides financial assurance for closure and post-closure care of the CCR surface impoundment or corrective action at a CCR surface impoundment; unless the Agency determines that the closure, post-closure care, or corrective action plan, or the amount of substituted financial assurance, is inadequate to provide closure and post-closure care or implement corrective action in compliance with this Part.

2) After closure and post-closure care have been completed in accordance with the plans and requirements of this Part or after the completion of corrective action at a CCR surface impoundment in accordance with this Part, the Agency must refund any unspent money that was paid into the Coal Combustion Residual Surface Impoundment Financial Assurance Fund by the surety, subject to appropriation of funds by the Illinois General Assembly.

Section 845.980 Surety Bond Guaranteeing Performance

a) An owner or operator may satisfy the requirements of this Subpart by obtaining a surety bond that conforms to the requirements of this Section and submitting the bond to the Agency.

b) The surety company issuing the bond must, at a minimum, be among those listed as acceptable sureties on federal bonds in Circular 570 of the U.S. Department of the Treasury. Circular 570 is available on the Internet from the following website: https://fiscal.treasury.gov/surety-bonds/circular-570.html.

c) The surety bond must be on forms prescribed by the Agency.

d) Any payments made under the bond will be placed in the Coal Combustion Residual Surface Impoundment Financial Assurance Fund within the State Treasury.

e) Conditions

1) The bond must guarantee that the owner or operator will:

A) Provide closure and post-closure care in accordance with the approved closure and post-closure care plans and, if the bond is a corrective action bond, provide corrective action in accordance with this Part; and

B) Provide alternative financial assurance, as specified in this Subpart, and obtain the Agency's written approval of the assurance provided within 90 days after receipt by both the owner or operator and the Agency of a notice from the surety that the bond will not be renewed for another term.

2) The surety will become liable on the bond obligation when, during the term of the bond, the owner or operator fails to perform as guaranteed by the bond. The owner or operator fails to perform when the owner or operator:

A) Abandons the CCR surface impoundment;

B) Is adjudicated bankrupt;

C) Fails to initiate closure of the CCR surface impoundment or post-closure care or corrective action when ordered to do so by the Board under Title VIII of the Act (Enforcement), or when ordered to do so by a court of competent jurisdiction;

D) Notifies the Agency that it has initiated closure or corrective action, or initiates closure or corrective action, but fails to close the CCR surface impoundment or provide post-closure care or corrective action in accordance with the Agency-approved closure and post-closure care or corrective action plans;

E) For a corrective action bond, fails to implement or complete corrective action at a CCR surface impoundment in accordance with Section 845.670; or

F) Fails to, within 90 days after receipt by both the owner or operator and the Agency of a notice from the surety that the bond will not be renewed for another term:

i) Provide alternative financial assurance, as specified in this Subpart; and

ii) Obtain the Agency's written approval of the assurance.

3) Upon failure of the owner or operator to perform as guaranteed by the bond, the surety must have the option of:

A) providing closure and post-closure care in accordance with the approved closure and post-closure care plans;

B) carrying out corrective action in accordance with the corrective action plan; or

C) paying the penal sum.

f) Penal Sum

1) The penal sum of the bond must be in an amount at least equal to the current cost estimate.

2) Whenever the current cost estimate decreases, the penal sum may be reduced to the amount of the current cost estimate following written approval by the Agency.

3) Whenever the current cost estimate increases to an amount greater than the penal sum, the owner or operator, within 90 days after the increase, must either cause the penal sum to be increased to an amount at least equal to the current cost estimate and submit evidence of that increase to the Agency or obtain other financial assurance, as specified in this Subpart, and submit evidence of the alternative financial assurance to the Agency.

g) Term

1) The bond must be issued for a term of at least one year and must not be cancelable during that term.

2) The surety bond must provide that, on the current expiration date and on each successive expiration date, the term of the surety bond will be automatically extended for a period of at least one year unless, at least 120 days before the current expiration date, the surety notifies both the owner or operator and the Agency by certified mail of a decision not to renew the bond. Under the terms of the surety bond, the 120 days will begin on the date when both the owner or operator and the Agency have received the notice, as evidenced by the return receipts.

3) The Agency must release the surety by providing written authorization for termination of the bond to the owner or operator and the surety when either of the following occurs:

A) An owner or operator substitutes alternative financial assurance, as specified in this Subpart; or

B) The Agency releases the owner or operator from the requirements of this Subpart in accordance with Section 845.920(b).

h) Cure of Default and Refunds

1) The Agency must release the surety if, after the surety becomes liable on the bond, the owner or operator or another person provides financial assurance for closure and post-closure care of the CCR surface impoundment or corrective action at a CCR surface impoundment; unless the Agency determines that the closure, post-closure care, or corrective action plan, or the amount of substituted financial assurance, is inadequate to provide closure and post-closure care or implement corrective action in compliance with this Part.

2) After closure and post-closure care have been completed in accordance with the plans and requirements of this Part or after the completion of corrective action at a CCR surface impoundment in accordance with this Part, the Agency must refund any unspent money that was paid into the Coal Combustion Residual Surface Impoundment Financial Assurance Fund by the surety, subject to appropriation of funds by the Illinois General Assembly.

i) The surety will not be liable for deficiencies in the performance of closure, post-closure care, or corrective action by the owner or operator after the Agency releases the owner or operator from the requirements of this Subpart.

Section 845.990 Letter of Credit

a) An owner or operator may satisfy the requirements of this Subpart by obtaining an irrevocable standby letter of credit that conforms to the requirements of this Section and submitting the letter to the Agency.

b) The issuing institution must be an entity that has the authority to issue letters of credit and:

1) Whose letter of credit operations are regulated by the Illinois Department of Financial and Professional Regulation under the Illinois Banking Act [205 ILCS 5]; or

2) Whose deposits are insured by the Federal Deposit Insurance Corporation.

c) Forms

1) The letter of credit must be on forms prescribed by the Agency.

2) The letter of credit must be accompanied by a letter from the owner or operator, referring to the letter of credit by number, the name and address of the issuing institution, and the effective date of the letter, and providing the following information: the name and address of the CCR surface impoundment, the identification number (see Section 845.130), and the

amount of funds assured by the letter of credit for closure and post-closure care of the CCR surface impoundment, or for corrective action at the CCR surface impoundment.

d) Any amounts drawn by the Agency under the letter of credit will be deposited in the Coal Combustion Residual Surface Impoundment Financial Assurance Fund within the State Treasury.

e) Conditions on Which the Agency Must Draw on the Letter of Credit:

1) The Agency must draw on the letter of credit if the owner or operator fails to perform closure or post-closure care in accordance with the approved closure and post-closure care plans or fails to perform corrective action at a CCR surface impoundment in accordance with this Part.

2) The Agency must draw on the letter of credit if the owner or operator:

A) Abandons the CCR surface impoundment;

B) Is adjudicated bankrupt;

C) Fails to initiate closure of the CCR surface impoundment or post-closure care or corrective action when ordered to do so by the Board under Title VIII of the Act (Enforcement), or when ordered to do so by a court of competent jurisdiction;

D) Notifies the Agency that it has initiated closure or corrective action, or initiates closure or corrective action, but fails to provide closure and post-closure care or corrective action in accordance with the Agency-approved closure and post-closure care or corrective action plans;

E) For a corrective action letter of credit, fails to implement or complete corrective action at a CCR surface impoundment in accordance with Section 845.670; or

F) Fails to, within 90 days after receipt by both the owner or operator and the Agency of a notice from the surety that the bond will not be renewed for another term:

i) Provide alternative financial assurance, as specified in this Subpart; and

ii) Obtain the Agency's written approval of the assurance.

3) If the owner or operator does not establish alternative financial assurance,

as specified in this Subpart, and obtain written approval of that alternative assurance from the Agency within 90 days after receipt by both the owner or operator and the Agency of a notice of expiration from the issuing institution (see subsection (g)(2)), the Agency must draw on the letter of credit. During the last 30 days of a notice of expiration, the Agency must draw on the letter of credit if the owner or operator has failed to provide alternative financial assurance, as specified in this Section, and obtain from the Agency written approval of that assurance.

f) Amount

1) The letter of credit must be issued in an amount at least equal to the current cost estimate.

2) Whenever the current cost estimate decreases, the amount of credit may be reduced to the amount of the current cost estimate following written approval by the Agency.

3) Whenever the current cost estimate increases to an amount greater than the amount of the credit, the owner or operator, within 90 days after the increase, must either cause the amount of the credit to be increased to an amount at least equal to the current cost estimate and submit evidence of that increase to the Agency or obtain other financial assurance, as specified in this Subpart, to cover the increase and submit evidence of the alternative financial assurance to the Agency.

g) Term

1) The letter of credit must be issued for a term of at least one year and must be irrevocable during that term.

2) The letter of credit must provide that, on the current expiration date and on each successive expiration date, the letter of credit will be automatically extended for a period of at least one year unless, at least 120 days before the current expiration date, the issuing institution notifies both the owner or operator and the Agency by certified mail of a decision not to extend the letter of credit for another term. Under the terms of the letter of credit, the 120 days will begin on the date when both the owner or operator and the Agency have received the notice, as evidenced by the return receipts.

3) The Agency must return the letter of credit to the issuing institution for termination when either of the following occurs:

A) An owner or operator substitutes alternative financial assurance, as specified in this Subpart; or

B) The Agency releases the owner or operator from the requirements of this Subpart in accordance with Section 845.920(b).

h) Cure of Default and Refunds

1) The Agency must release the financial institution if, after the Agency is allowed to draw on the letter of credit, the owner or operator or another person provides financial assurance for closure and post-closure care of the CCR surface impoundment or corrective action at a CCR surface impoundment; unless the Agency determines that the closure, post-closure care, or corrective action plan, or the amount of substituted financial assurance, is inadequate to provide closure and post-closure care or implement corrective action in compliance with this Part.

2) After closure and post-closure care have been completed in accordance with the plans and requirements of this Part or after the completion of corrective action at a CCR surface impoundment in accordance with this Part, the Agency must refund any unspent money that was drawn and paid into the Coal Combustion Residual Surface Impoundment Financial Assurance Fund by the financial institution, subject to appropriation of funds by the Illinois General Assembly.

DOCUMENT
10

Luminant

Illinois Power Generating Company
1500 Eastport Plaza Dr.
Collinsville, IL 62234

October 25, 2021

Illinois Environmental Protection Agency
DWPC – Permits MC #15
Attn: Part 845 Coal Combustion Residual Rule Submittal
1021 North Grand Avenue East
P.O. Box 19276
Springfield, IL 62794-9276

Re: Newton Power Plant Primary Ash Pond; IEPA ID # W0798070001-01

Dear Mr. LeCrone:

In accordance with 35 I.A.C. § 845.200, Illinois Power Generating Company (IPGC) is submitting an operating permit application for the Newton Power Plant Primary Ash Pond (IEPA ID # W0798070001-01). One hardcopy and one digital copy are provided with this submittal.

The permit application was prepared in accordance with 35 I.A.C. § 845.230(d)(2) (Existing, Inactive and Inactive Closed CCR Surface Impoundment that have not completed an Agency approved closure before July 30, 2021). This submittal includes the completed permit forms as required by § 845.210.

Sincerely,

Cynthia Vodopivec
SVP-Environmental Health and Safety

Enclosures

Prepared for

Illinois Power Generating Company
1500 Eastport Plaza Drive
Collinsville, Illinois 62234

INITIAL OPERATING PERMIT

NEWTON ASH POND

Prepared by

BURNS
McDONNELL

425 South Woods Mill Road, Suite 300
St. Louis, MO 63017

October 25, 2021

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ATTACHMENTS

1. INTRODUCTION

Illinois Power Generating Company operates the coal-fired Newton Power Plant located in Jasper County, Illinois. The IEPA assigned identification number assigned to this impoundment is: W0798070001-01 for the Primary Ash Pond. The National Inventory of Dams (NID) number assigned for the Primary Ash Pond by the Illinois Department of Natural Resources (IDNR) is IL50719.

This initial operating permit application was developed in accordance with 35 Ill. Admin. Code 845, Standards for the Disposal of Coal Combustion Residuals in Surface Impoundments (Part 845).

This initial operating permit application is for the Primary Ash Pond.

1.1. Facility Information

> Section 845.210(b)(1): *All permit applications must contain the name, address, email address and telephone number of the operator, or duly authorized agent, and the property owner to whom all inquiries and correspondence shall be addressed.*

Facility:	Newton Ash Pond Newton Power Plant 6725 North 500th Street Newton, IL 62448
Owner/Operator:	Illinois Power Generating Company 1500 Eastport Plaza Drive Collinsville, Illinois 62234

1.2. Owner Signatures

> <u>Section 845.210(b)(2):</u> *All permit applications must be signed by the owner, operator or a duly authorized agent of the operator.*

The owner of the Newton Power Plant is a corporation.

> <u>Section 845.210(b)(3):</u> *An application submitted by a corporation must be signed by a principal executive officer of at least the level of vice president, or his or her duly authorized representative, if that representative is responsible for the overall operation of the facility described in the application form..*

The signature of Cynthia Vodopivec on behalf of Illinois Power Generating Company can be found in the permit applications located in Section 3.

1.3. Legal Description

> <u>Section 845.210(c):</u> *All permit applications must contain a legal description of the facility boundary and a description of the boundaries of all units included in the facility.*

A legal description has been developed in compliance with Section 845.210(c) and is included in Attachment A.

1.4. Previous Assessments

> <u>Section 845.210(d):</u> *Previous Assessments, Investigations Plans, and Programs*

Previous assessments were performed in accordance with 40 CFR § 257 and are referenced within the permit application and included in the appropriate Attachments.

> <u>Section 845.210(d)(1):</u> *The Agency may approve the use of any hydrogeologic site investigation or characterization, groundwater monitoring well or system, or groundwater monitoring plan, bearing the seal and signature of an Illinois Licensed Professional Geologist or Licensed Professional Engineer, completed before April 21, 2021 to satisfy the requirements of this Part.*

A previous hydrogeologic site investigation or characterization, groundwater monitoring well or system, or groundwater monitoring plan have been completed with a seal from an Illinois Licensed Professional Geologist or Licensed Professional Engineer. However, field investigations have been completed that supplement that work that will be utilized in the following sections of this report.

> *<u>Section 845.210(d)(2):</u> For existing CCR surface impoundments, the owner or operator of the CCR surface impoundment may use a previously completed location restriction demonstration required by Section 845.300 (Placement Above the Uppermost Aquifer), Section 845.310 (Wetlands), Section 845.320 (Fault Areas), Section 845.330 (Seismic Impact Zones), and Section 845.340 (Unstable Areas) provided that the previously completed assessments meet the applicable requirements of those Sections.*

Previous assessments are provided for Section 845.300 (Placement Above the Uppermost Aquifer), Section 845.310 (Wetlands), Section 845.320 (Fault Areas), Section 845.330 (Seismic Impact Zones), and Section 845.340 (Unstable Areas) in Attachment D.

> *<u>Section 845.210(d)(3):</u> For existing CCR surface impoundments, the owner or operator of the CCR surface impoundment may use a previously completed assessment to serve as the initial assessment required by Section 845.440 (Hazard Potential Classification Assessment), Section 845.450 (Structural Stability Assessment) and Section 845.460 (Safety Factor Assessment) provided that the previously completed assessment: A) Was not completed more than five years ago; and B) Meets the applicable requirements of those Sections.*

Previous assessments are provided for Section 845.440 (Hazard Potential Classification Assessment), Section 845.450 (Structural Stability Assessment) and Section 845.460 (Safety Factor Assessment) in Attachments O, P, and Q respectively. The addendum and certification for the Hazard Potential Classification Assessment, Structural Stability Assessment and Safety Factor Assessment are located in Attachment U.

> *<u>Section 845.210(d)(4):</u> For inactive closed CCR surface impoundments, the owner or operator of the CCR surface impoundment may use a post-closure care plan previously approved by the Agency.*

No post-closure care plan was previously approved by the Agency.

2. OPERATING PERMIT

2.1. Initial Operating Permit

> <u>Section 845.230(d):</u> *Initial Operating Permit for Existing, Inactive and Inactive Closed CCR Surface Impoundments*

The Newton Primary Ash Pond as defined by IEPA is an existing CCR surface impoundment that has not completed post-closure care. Per Part 845, Dynegy is submitting an initial operating permit application to IEPA by October 31, 2021. The following sections contain information or references to documents required for the Operating Permit application (Section 845.230).

2.2. History of Construction

> <u>Section 845.230(d)(2)(A):</u> *The history of construction specified in Section 845.220(a)(1);*

The history of construction prepared in 2016 pursuant to 40 CFR § 257.73(c) is provided in Attachment B. An amendment to the history of construction has been prepared in compliance with Section 845.220(a)(1) and is provided in Attachment U.

2.3. Chemical Constituents

> <u>Section 845.230(d)(2)(B):</u> *An analysis of the chemical constituents found within the CCR to be placed in the CCR surface impoundment;*

An analysis of the chemical constituents found within the CCR placed within the Newton Primary Ash Pond is provided in Attachment C.

> <u>Section 845.230(d)(2)(C):</u> *An analysis of the chemical constituents of all waste streams, chemical additives and sorbent materials entering or contained in the CCR surface impoundment;*

An analysis of the chemical constituents of all waste streams, chemical additives and sorbent materials entering or contained within the Newton Primary Ash Pond is provided in Attachment C.

2.4. Location Standards Demonstration

> <u>Section 845.230(d)(2)(D):</u> *A demonstration that the CCR surface impoundment, as built, meets, or an explanation of how the CCR surface impoundments fails to meet, the location standards in the following Sections:*

The Newton Primary Ash Pond location standards as specified in Section 845.230(d)(2)(D) are described in the following sections.

<u>Section 845.230(d)(2)(D)(i):</u> Placement Above the Uppermost Aquifer;

The previous upper aquifer demonstration was certified by a qualified professional engineer stating that the demonstration meets the requirements of 40 C.F.R. § 257.60. The requirements described in 40 C.F.R. § 257.60 are identical to the requirements contained in Section 845.300. Pursuant to Section 845.210(d)(2), a certification is not required for this demonstration. The previously completed upper aquifer demonstration is included in Attachment D.

<u>Section 845.230(d)(2)(D)(ii):</u> Wetlands;

The previous wetlands demonstration was certified by a qualified professional engineer stating that the demonstration meets the requirements of 40 C.F.R. § 257.61. The requirements described in 40 C.F.R. § 257.61 are identical to the requirements contained in Section 845.310. Pursuant to Section 845.210(d)(2), a certification is not required for this demonstration. The previously completed wetlands demonstration is included in Attachment D.

<u>Section 845.230(d)(2)(D)(iii):</u> Fault Areas;

The previous fault area demonstration was certified by a qualified professional engineer stating that the demonstration meets the requirements of 40 C.F.R. § 257.62. The requirements described in 40 C.F.R. § 257.62 are identical to the requirements contained in Section 845.320. Pursuant to Section 845.210(d)(2), a certification is not required for this demonstration. The previously completed fault area demonstration is included in Attachment D.

<u>Section 845.230(d)(2)(D)(iv):</u> Seismic Impact Zone; and

The previous seismic impact zone demonstration was certified by a qualified professional engineer stating that the demonstration meets the requirements of 40 C.F.R. § 257.63. The requirements described in 40 C.F.R. § 257.63 are identical to the requirements contained in Section 845.330. Pursuant to Section 845.210(d)(2), a certification is not required for this demonstration. The previously completed seismic impact zone demonstration is included in Attachment D.

<u>Section 845.230(d)(2)(D)(v):</u> Unstable Areas and Floodplains;

The previous unstable area demonstration was certified by a qualified professional engineer stating that the demonstration meets the requirements of 40 C.F.R. § 257.64. The requirements described in 40 C.F.R. § 257.64 are identical to the requirements contained in Section 845.340. Pursuant to Section 845.210(d)(2), a certification is not required for the unstable area demonstration. The previously completed unstable area demonstration is included in Attachment D.

The boundaries of the impoundment were determined by a survey conducted by a professional surveyor licensed in the State of Illinois. The boundaries of the Primary Ash Pond were compared to the existing FEMA floodplain map, and it was determined that the Primary Ash Pond is Pond is located within Zone A of the floodplain according to the 1985 FEMA Floodplain mapping. In order to determine that: "generally accepted engineering practices have been incorporated into the design of the CCR surface impoundment to ensure that the CCR surface impoundment will not restrict the flow of the base flood, reduce the temporary water storage capacity of a floodplain, or result in washout of CCR," the following engineering was involved:

1. Determine the base flood elevation (BFE) and compare to the ash pond embankment elevations,
2. Determine the surface impoundment will not restrict the temporary water storage capacity of the floodplain. and
3. Result in a washout of CCR.

A certification attesting to this is provided in Attachment D.

2.5. Permanent Markers

<u>Section 845.230(d)(2)(E):</u> Evidence of permanent markers required by Section 845.130 have been installed;

Evidence of permanent markers at the Newton Primary Ash Pond as required by Section 845.130 is provided in Attachment E.

2.6. Slope Maintenance

<u>Section 845.230(d)(2)(F):</u> Documentation that the CCR surface impoundment, if not incised, will be operated and maintained with one of the forms of slope protection specified in Section 845.430;

The Newton Primary Ash Pond is not incised. Documentation of slope protection as required by Section 845.430 is provided in Attachment J.

2.7. Initial Emergency Action Plan

<u>Section 845.230(d)(2)(G):</u> Initial Emergency Action Plan and accompanying certification (see Section 845.520(e));

The initial emergency action plan and certification has been completed as specified by Section 845.520(e) and is provided in Attachment F.

2.8. Fugitive Dust Control Plan

<u>Section 845.230(d)(2)(H):</u> Fugitive dust control plan and accompanying certification (see Section 845.500(b)(7));

The fugitive dust control plan and certification has been completed as specified by Section 845.500(b)(7) and is provided in Attachment G.

2.9. Groundwater Monitoring

<u>Section 845.230(d)(2)(I):</u> Groundwater monitoring information:

The groundwater monitoring information for the Newton Primary Ash Pond is described in the following sections.

<u>Section 845.230(d)(2)(I)(i):</u> Hydrogeologic site characterization (see Section 845.620);

Hydrogeologic site characterization for the Newton Primary Ash Pond is provided in Attachment H.

<u>Section 845.230(d)(2)(I)(ii):</u> Design and construction plans of a groundwater monitoring system (see Section 845.630);

Design and construction plans of a groundwater monitoring system are provided in Attachment I.

<u>Section 845.230(d)(2)(I)(iii):</u> A groundwater sampling and analysis program that includes selection of the statistical procedures to be used for evaluating groundwater monitoring data (see Section 845.640); and

A groundwater sampling and analysis program that meets the requirements of Section 845.640 is provided in Attachment I.

Section 845.230(d)(2)(I)(iv): Proposed groundwater monitoring program that includes a minimum of eight independent samples for each background and downgradient well (see Section 845.650(b));

A proposed groundwater monitoring program that meets the requirements of Section 845.650(b) is provided in Attachment I.

2.10. Initial Post-Closure Care Plan

Section 845.230(d)(2)(K): Initial written post-closure care plan, if applicable (see Section 845.780(d));

The Newton Primary Ash Pond closure will be completed by capping the CCR in place. The initial post closure care plan was developed in accordance with Section 845.780 and is provided in Attachment K.

2.11. History of Groundwater Exceedances

Section 845.230(d)(2)(M): History of known exceedances of the groundwater protection standards in Section 845.600, and any corrective action taken to remediate the groundwater;

A history of known exceedances and any corrective action taken is provided in Attachment M.

2.12. Financial Assurance Requirements

Section 845.230(d)(2)(N): A certification that the owner or operator meets the financial assurance requirements of Subpart I;

A certification meeting the requirement of Section 845.230(d)(2)(N) stating that the Owner meets the financial assurance requirements of *Subpart I* is provided in Attachment N.

2.13. Hazard Potential Classification

Section 845.230(d)(2)(O): Hazard potential classification assessment and accompanying certification (see Section 845.440(a)(2));

The previous Hazard Potential Classification Assessment completed in compliance with 40 CFR §257.73(a) is provided in Attachment O. The addendum to the Hazard Potential Classification Assessment and certification as required by Section 845.440(a) is provided in Attachment U.

2.14. Structural Stability Assessment

> *Section 845.230(d)(2)(P): Structural stability assessment and accompanying certification (see Section 845.450(c));*

The previous Structural Stability Assessment completed in compliance with 40 CFR §257.73(d) is provided in Attachment P. The addendum to the Structural Stability Assessment and certification as required by Section 845.450(c) is provided in Attachment U.

2.15. Safety Factor Assessment

> *Section 845.230(d)(2)(Q): Safety factor assessment and accompanying certification (see Section 845.460(b));*

The previous Safety Factor Assessment completed in compliance with 40 CFR §257.73(e) is provided in Attachment Q. The addendum to the Safety Factor Assessment and certification as required by Section 845.460(b) is provided in Attachment U.

2.16. Inflow Design Flood Control System Plan

> *Section 845.230(d)(2)(R): Inflow design flood control system plan and accompanying certification (see Section 845.510(c)(3));*

The previous Inflow Design Flood Control System Plan Assessment completed in compliance with 40 CFR §257.82 is provided in Attachment R. The addendum to the Inflow Design Flood Control Plan Assessmentas required by Section 845.510(c)(3) is provided in Attachment U.

2.17. Safety and Health Plan

> *Section 845.230(d)(2)(S): Safety and health plan (see Section 845.530); and*

The safety and health plan in accordance with Section 845.530 is included in Attachment S.

2.18. Proposed Closure Priority Categorization

> *Section 845.230(d)(2)(T): For CCR surface impoundments required to close under 845.700, the proposed closure priority categorization required by Section 845.700(g).*

A CCR Surface Impoundment Category Designation and Justification letter was submitted to IEPA on May 19, 2021. The Newton Primary Ash Pond was designated as Category 5 Existing CCR surface impoundment with exceedances of the groundwater protection standards in Section 845.600. This letter is provided in Attachment T.

3. PERMIT APPLICATION

All permit applications must be made on the forms prescribed by the Agency and must be mailed or delivered to the address designated by the Agency on the forms. The permit applications (CCR-1 and CCR-2E) are provided below.

Form CCR 1

Illinois Environmental Protection Agency
CCR Surface Impoundment Permit Application
Form CCR 1 – General Provisions

Bureau of Water ID Number:
W0798070001
CCR Permit Number:
Initial Permit
Facility Name:
Newton Power Plant

For IEPA Use Only

SECTION 1: FACILITY, OPERATOR, AND OWNER INFORMATION (35 Ill. Adm. Code 845.210(b))

Facility, Operator, and Owner Information

1.1	Facility Name		
	Illinois Power Generating Company - Newton Power Plant		
1.2	Illinois EPA CCR Permit Number (if applicable)		
	Initial Permit		
1.3	Facility Contact Information		
	Name (first and last) Phil Morris	Title Senior Director - Environmental	Phone Number 618-343-7794
	Email address phil.morris@vistracorp.com		
1.4	Facility Mailing Address		
	Street or P.O. box 1500 Eastport Plaza Dr		
	City or town Collinsville	State IL	Zip Code 62234
1.5	Facility Location		
	Street, route number, or other specific identifier 6725 North 500th Street		
	County name Jasper	County code (if known)	
	City or town Newton	State IL	Zip Code 62448
1.6	Name of Owner/Operator		
	Illinois Power Generating Company		

Facility, Operator, and Owner Info

1.7	Owner/Operator Contact Information		
	Name (first and last) Phil Morris	Title Senior Director - Environmental	Phone Number 618-343-7794
	Email address phil.morris@vistracorp.com		
1.8	Owner/Operator Mailing Address		
	Street or P.O. box 1500 Eastport Plaza Dr		
	City or town Collinsville	State IL	Zip Code 62234

SECTION 2: LEGAL DESCRIPTION (35 Ill. Adm. Code 845.210(c))

Legal Description

2.1	Legal Description of the facility boundary
	See Attachment A.

SECTION 3: PUBLICLY ACCESSIBLE INTERNET SITE REQUIREMENTS (35 Ill. Adm. Code 845.810)

Internet Site

3.1	Web Address(es) to publicly accessible internet site(s) (CCR website)			
	www.luminant.com/illinois-ccr			
3.2	Is/are the website(s) titled "Illinois CCR Rule Compliance Data and Information"			
	☑	Yes	☐	No

SECTION 4: IMPOUNDMENT IDENTIFICATION

Impoundment Identification

4.1	List all the impoundment identification numbers for your facility and check the corresponding box to indicate that you have attached a written description for each impoundment.		
	W0798070001-01 (see Attachment A)	☑	Attached written description
		☐	Attached written description
		☐	Attached written description
		☐	Attached written description
		☐	Attached written description
		☐	Attached written description

	☐	Attached written description
	☐	Attached written description
	☐	Attached written description
	☐	Attached written description

SECTION 5: CHECKLIST AND CERTIFICATION STATEMENT

Checklist and Certification Statement

5.1 In Column 1 below, mark the sections of Form 1 that you have completed and are submitting with your application. For each section, specify in Column 2 any attachments that you are enclosing.

Column 1		**Column 2**	
Section 1: Facility, Operator, and Owner Information	☑	w/attachments	☐
Section 2: Legal Description	☑	w/attachments	☑
Section 3: Publicly Accessible Internet Site Requirement	☑	w/attachments	☐
Section 4: Impoundment Identification	☑	w/attachments	☑

5.2 **Certification Statement**

I certify under penalty of law that this document and all attachments were prepared under my direction or supervision in accordance with a system designed to assure that qualified personnel properly gather and evaluate the information submitted. Based on my inquiry of the person or persons who manage the system, or those persons directly responsible for gathering the information, the information submitted is, to the best of my knowledge and belief, true, accurate, and complete. I am aware that there are significant penalties for submitting false information, including the possibility of fine and imprisonment for knowing violations.

Name (print or type first and last name) of Owner/Operator Cynthia Vodopivec	Official Title SVP - Environmental
Signature	Date Signed 10/25/2021

Form CCR 2E

Illinois Environmental Protection Agency

CCR Surface Impoundment Permit Application

Form CCR 2E – Initial Operating Permit for Existing or Inactive CCR Surface Impoundments That Have Not Completed an Agency-approved Closure Before July 30, 2021

Bureau of Water ID Number:
W0798070001

CCR Permit Number:
Initial Permit

Facility Name:
Newton Power Plant

For IEPA Use Only

SECTION 1: CONSTRUCTION HISTORY (35 Ill. Adm. Code 845.220 AND 35 Ill. Adm. Code 845.230)

Construction History

1.1	CCR surface impoundment name.
	Primary Ash Pond
1.2	Identification number of the CCR surface impoundment (if one has been assigned by the Agency).
	W0798070001-01
1.3	Description of the boundaries of the CCR surface impoundment (35 Ill. Adm. Code 845.210(c)).
	See Attachment A.
1.4	State the purpose for which the CCR surface impoundment is being used.
	See Attachment B.
1.5	How long has the CCR surface impoundment been in operation?
	See Attachment B.
1.6	List the types of CCR that have been placed in the CCR surface impoundment.
	See Attachment C.

Construction History (Continued)	1.7	List name of the watershed within which the CCR surface impoundment is located.	
		See Attachment B.	
	1.8	Size in acres of the watershed within which the CCR surface impoundment is located.	
		See Attachment B.	
	1.9	Check the corresponding box to indicate that you have attached the following:	
		☑	Description of the physical and engineering properties of the foundation and abutment materials on which the CCR surface impoundment is constructed.
		☑	Description of the type, size, range, and physical and engineering properties of the materials used in constructing each zone or stage of the CCR surface impoundment.
		☑	Describe the method of site preparation and construction of each zone of the CCR surface impoundment.
		☑	A listing of the approximate dates of construction of each successive stage of construction of the CCR surface impoundment.
		☑	Drawing satisfying the requirements of 35 Ill. Adm. Code 845.220(a)(1)(F).
		☑	Description of the type, purpose, and location of existing instrumentation.
		☑	Area capacity curves for the CCR Impoundment.
		☑	Description of each spillway and diversion design features and capacities and provide the calculations used in their determination.
		☑	Construction specifications and provisions for surveillance, maintenance, and repair of the CCR surface impoundment.
	1.10.1	Is there any record or knowledge of structural instability of the CCR surface impoundment?	
		☐ Yes	☑ No
	1.10.2	If you answered yes to Item 1.10.1, provide detailed explanation of the structural instability.	

SECTION 2: ANALYSIS OF CHEMICAL CONSTITUENTS (35 Ill. Adm. Code 845.230(d)(2)(B))

Constituents	2.1	Check the corresponding boxes to indicate you have attached the following:	
		☑	An analysis of the chemical constituents found within the CCR to be placed in the CCR surface impoundment.
		☑	An analysis of the chemical constituents of all waste streams, chemical additives and sorbent materials entering or contained in the CCR surface impoundment.

SECTION 3: DEMONSTRATIONS AND CERTIFICATIONS (35 Ill. Adm. Code 845.230(d)(2)(D))

Demonstrations

3.1 Indicate whether you have attached a demonstration that the CCR surface impoundment, as built, meets, or an explanation of how the CCR surface impoundments fails to meet, the location standards in the following sections:

35 Ill. Adm. Code 845.300 (Placement Above the Uppermost Aquifer)	☑	Demonstration	☐	Explanation
35 Ill. Adm. Code 845.310 (Wetlands)	☑	Demonstration	☐	Explanation
35 Ill. Adm. Code 845.320 (Fault Areas)	☑	Demonstration	☐	Explanation
35 Ill. Adm. Code 845.330 (Seismic Impact Zones)	☑	Demonstration	☐	Explanation
35 Ill. Adm. Code 845.340 (Unstable Areas and Floodplains)	☑	Demonstration	☐	Explanation

SECTION 4: ATTACHMENTS

Attachments

4.1 Check the corresponding boxes to indicate that you have attached the following:

☑	Evidence that the permanent markers required by 35 Ill. Adm. Code 845.130 have been installed.
☑	Documentation that the CCR surface impoundment, if not incised, will be operated and maintained with one of the forms of slope protection specified in 35 Ill. Adm. Code 845.430.
☑	Initial Emergency Action Plan and accompanying certification required by 35 Ill. Adm. Code 845.520(e).
☑	Fugitive dust control plan and accompanying certification required by 35 Ill. Adm. Code 845.500(b)(7).
☐	Preliminary written closure plan as specified in 35 Ill. Adm. Code 845.720(a).
☑	Initial written post-closure care plan as specified in 35 Ill. Adm. Code 845.780(d), if applicable.
☐	A certification as specified in 35 Ill. Adm. Code 845.400(h), or a statement that the CCR surface impoundment does not have a liner than meets the requirements of 35 Ill. Adm. Code 845.400(b) or (c).
☑	History of known exceedances of the groundwater protection standards in 35 Ill. Adm. Code 845.600, and any corrective action taken to remediate the groundwater.
☑	Safety and health plan, as required by 35 Ill. Adm. Code 845.530.
☑	For CCR surface impoundments required to close under 35 Ill. Adm. Code 845.700, the proposed closure priority categorization required by 35 Ill. Adm. Code 845.700(g).

SECTION 5: GROUNDWATER MONITORING

Groundwater

5.1 Check the corresponding boxes to indicate you have attached the following groundwater monitoring information:

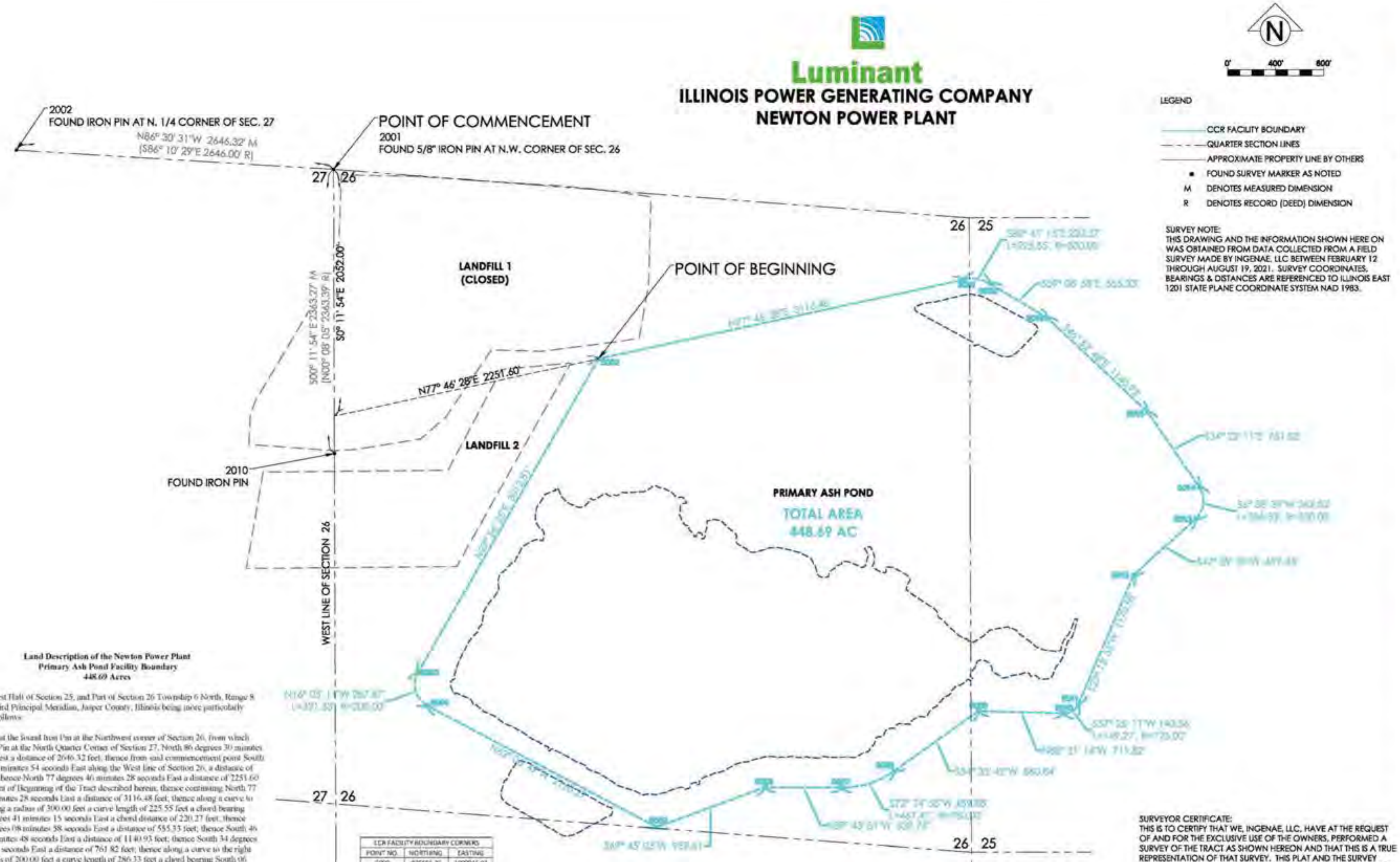
☑	A hydrogeologic site characterization meeting the requirements of 35 Ill. Adm. Code 845.620.
☑	Design and construction plans of a groundwater monitoring system meeting the requirements of 35 Ill. Adm. Code 845.630.

		☑	A groundwater sampling and analysis program that includes section of the statistical procedures to be used for evaluating groundwater monitoring data, required by 35 Ill. Adm. Code 845.640.
		☑	Proposed groundwater monitoring program that includes a minimum of eight independent samples for each background and downgradient well, required by 35 Ill. Adm. Code 845.650(b).
SECTION 6: CERTIFICATIONS			
Certifications	6.1	Check the corresponding boxes to indicate you have attached the following certifications:	
		☑	A certification that the owner or operator meets the financial assurance requirements of Subpart I, as required by 35 Ill. Adm. Code 845.230(d)(2)(N).
		☑	Hazard potential classification assessment and accompanying certifications required by 35 Ill. Adm. Code 845.440(a)(2).
		☑	Structural stability assessment and accompanying certification, required by 35 Ill. Adm. Code 845.450(c).
		☑	Safety factor assessment and accompanying certification, as required by 35 Ill. Adm. Code 845.460(b).
		☑	Inflow design flood control system plan and accompanying certification, as required by 35 Ill. Adm. Code 845.510(c)(3).

ATTACHMENT A

October 2021

Luminant
ILLINOIS POWER GENERATING COMPANY
NEWTON POWER PLANT



LEGEND

CCR FACILITY BOUNDARY
QUARTER SECTION LINES
APPROXIMATE PROPERTY LINE BY OTHERS
■ FOUND SURVEY MARKER AS NOTED
M DENOTES MEASURED DIMENSION
R DENOTES RECORD (DEED) DIMENSION

SURVEY NOTE:
THIS DRAWING AND THE INFORMATION SHOWN HERE ON WAS OBTAINED FROM DATA COLLECTED FROM A FIELD SURVEY MADE BY INGENAE, LLC BETWEEN FEBRUARY 12 THROUGH AUGUST 19, 2021. SURVEY COORDINATES, BEARINGS & DISTANCES ARE REFERENCED TO ILLINOIS EAST 1201 STATE PLANE COORDINATE SYSTEM NAD 1983.

Land Description of the Newton Power Plant
Primary Ash Pond Facility Boundary
448.69 Acres

Part of the West Half of Section 25, and Part of Section 26 Township 6 North, Range 8 East of the Third Principal Meridian, Jasper County, Illinois being more particularly described as follows:

Commencing at the found Iron Pin at the Northwest corner of Section 26, from which bears an Iron Pin at the North Quarter Corner of Section 27, North 86 degrees 30 minutes 31 seconds West a distance of 2646.32 feet; thence from said commencement point South 00 degrees 11 minutes 54 seconds East along the West line of Section 26, a distance of 2052.00 feet; thence North 77 degrees 46 minutes 28 seconds East a distance of 2251.60 feet to the Point of Beginning of the Tract described herein; thence continuing North 77 degrees 46 minutes 28 seconds East a distance of 3116.48 feet; thence along a curve to the right having a radius of 300.00 feet a curve length of 225.55 feet a chord bearing South 80 degrees 41 minutes 15 seconds East a chord distance of 220.27 feet; thence South 59 degrees 08 minutes 58 seconds East a distance of 555.33 feet; thence South 46 degrees 32 minutes 48 seconds East a distance of 1140.93 feet; thence South 34 degrees 22 minutes 11 seconds East a distance of 761.82 feet; thence along a curve to the right having a radius of 200.00 feet a curve length of 286.33 feet a chord bearing South 06 degrees 38 minutes 39 seconds West a chord distance of 262.50 feet; thence South 47 degrees 39 minutes 29 seconds West a distance of 697.45 feet; thence South 23 degrees 13 minutes 35 seconds West a distance of 1170.58 feet; thence along a curve to the right having a radius of 125.00 feet a curve length of 149.27 feet a chord bearing South 57 degrees 26 minutes 11 seconds West a chord distance of 140.56 feet; thence North 88 degrees 21 minutes 14 seconds West a distance of 711.82 feet; thence South 54 degrees 33 minutes 42 seconds West a distance of 860.84 feet; thence along a curve to the right having a radius of 750.00 feet a curve length of 467.41 feet a chord bearing South 72 degrees 24 minutes 55 seconds West a chord distance of 459.88 feet; thence North 89 degrees 43 minutes 51 seconds West a distance of 639.75 feet; thence South 69 degrees 45 minutes 03 seconds West a distance of 959.61 feet; thence North 62 degrees 06 minutes 47 seconds West a distance of 2160.27 feet; thence along a curve to the right having a radius of 200.00 feet a curve length of 321.33 feet a chord bearing North 16 degrees 05 minutes 11 seconds West a chord distance of 287.87 feet; thence North 29 degrees 56 minutes 25 seconds East a distance of 3012.81 feet to the Point of Beginning and containing 448.69 Acres.

CCR FACILITY BOUNDARY CORNERS		
POINT NO.	NORTHING	EASTING
5000	825556.26	1000045.93
5001	825591.31	999828.57
5002	824931.96	996782.70
5003	822321.22	995279.07
5004	822044.63	995358.84
5005	821034.21	997266.24
5006	821366.33	998168.55
5007	821353.33	998806.29
5008	821502.27	999246.68
5009	822001.40	999948.04
5010	821980.96	1000659.57
5011	822056.61	1000778.03
5012	823132.32	1001239.67
5013	823602.09	1001755.18
5014	823862.82	1001785.85
5015	824491.64	1001355.48
5016	825271.49	1000572.69

CONTROL MONUMENTATION				
POINT NO.	NORTHING	EASTING	ELEVATION	DESCRIPTION
2001	826507.13	994575.12	539.73	FOUND IRON PIN - N. 1/4 CORNER SEC. 27
2002	826668.81	993593.71	538.32	FOUND 5/8" IRON PIN - N.W. CORNER OF SEC. 26
2010	824143.94	994583.30	-	FOUND IRON PIN

SURVEYOR CERTIFICATE:
THIS IS TO CERTIFY THAT WE, INGENAE, LLC, HAVE AT THE REQUEST OF AND FOR THE EXCLUSIVE USE OF THE OWNERS, PERFORMED A SURVEY OF THE TRACT AS SHOWN HEREON AND THAT THIS IS A TRUE REPRESENTATION OF THAT SURVEY. THIS PLAT AND THE SURVEY FROM WHICH IT IS BASED WERE DONE IN ACCORDANCE WITH THE "MINIMUM STANDARDS OF PRACTICE" FOR LAND SURVEYING IN THE STATE OF ILLINOIS.

INGENAE, LLC
PROFESSIONAL DESIGN FIRM
LICENSE NO. 184.007588-0010

Sept. 20, 2021

MICHAEL J. GRAMINSKI
I.P.L.S. NO. 035.002901
EXPIRES: 11/30/2022

DATE

IngenAE
502 Earth City Plaza, Suite 120
Earth City, MO 63045
www.ingenae.com

Submissions / Revisions:	Date:
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Luminant

Project Name & Location:
NEWTON
POWER PLANT
6725 NORTH 500TH STREET
NEWTON, IL 62248

Drawing Name:
CCR FACILITY BOUNDARY EXHIBIT

Date: 09/09/2021	Project No.
Type: SITE	Drawing No. 1
Drawn By: CB	
Approved By: MG	
Scale: AS NOTED	

Luminant

ILLINOIS POWER GENERATING COMPANY
NEWTON POWER PLANT

0' 400' 800'

LEGEND

———	CCR FACILITY BOUNDARY
— - - —	QUARTER SECTION LINES
———	APPROXIMATE PROPERTY LINE BY OTHERS
●	FOUND SURVEY MARKER AS NOTED
M	DENOTES MEASURED DIMENSION
R	DENOTES RECORD (DEED) DIMENSION

SURVEY NOTE:
THIS DRAWING AND THE INFORMATION SHOWN HERE ON WAS OBTAINED FROM DATA COLLECTED FROM A FIELD SURVEY MADE BY INGENAE, LLC BETWEEN FEBRUARY 12 THROUGH AUGUST 19, 2021. SURVEY COORDINATES, BEARINGS & DISTANCES ARE REFERENCED TO ILLINOIS EAST 1201 STATE PLANE COORDINATE SYSTEM NAD 1983.

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Luminant

Project Name & Location:

NEWTON
POWER PLANT
6725 NORTH 500TH STREET
NEWTON, IL 62248

DO NOT SCALE PLANS
Copying, Printing, Software and other processes required to produce these prints can stretch or shrink the actual paper or layout. Therefore, scaling of this drawing may be inaccurate. Contact IngenAE with any need for additional dimensions or clarifications.

Drawing Name:
AERIAL
PHOTOGRAPHY

Date: 09/09/2021	Project No.
Type: SITE	Drawing No. 2
Drawn By: CB	
Approved By: MG	
Scale: AS NOTED	

ATTACHMENT B

October 2016

Illinois Power Generating Company
6725 North 500th Street
Newton, IL 62448

RE: History of Construction
USEPA Final CCR Rule, 40 CFR § 257.73(c)
Newton Power Station
Newton, Illinois

On behalf of Illinois Power Generating Company, AECOM has prepared the following history of construction for the Primary Ash Pond at the Newton Power Station in accordance with 40 CFR § 257.73(c).

BACKGROUND

40 CFR § 257.73(c)(1) requires the owner or operator of an existing coal combustion residual (CCR) surface impoundment that either (1) has a height of five feet or more and a storage volume of 20 acre-feet or more, or (2) has a height of 20 feet or more to compile a history of construction by October 17, 2016 that contains, to the extent feasible, the information specified in 40 CFR § 257.73(c)(1)(i)–(xii).

The history of construction presented herein was compiled based on existing documentation, to the extent that it is reasonably and readily available (see 80 Fed. Reg. 21302, 21380 [April 17, 2015]), and AECOM's site experience. AECOM's document review included record drawings, geotechnical investigations, etc. for the Primary Ash Pond at the Newton Power Station.

HISTORY OF CONSTRUCTION

§ 257.73(c)(1)(i): The name and address of the person(s) owning or operating the CCR unit; the name associated with the CCR unit; and the identification number of the CCR unit if one has been assigned by the state.

Owner: Illinois Power Generating Company

Address: 1500 Eastport Drive
Collinsville, IL 62234

CCR Unit: Primary Ash Pond

The Primary Ash Pond does not have a state assigned identification number.

§ 257.73(c)(1)(ii): The location of the CCR unit identified on the most recent USGS $7^1/_2$ or 15 minute topographic quadrangle map or a topographic map of equivalent scale if a USGS map is not available.

The location of the Primary Ash Pond has been identified on an USGS 7-1/2 minute topographic quadrangle map in **Appendix A**.

§ 257.73(c)(1)(iii): A statement of the purpose for which the CCR unit is being used.

The Primary Ash Pond is being used to store and dispose of bottom ash and economizer ash and to clarify non-CCR plant process wastewater. A portion of the bottom ash is reclaimed from the Primary Ash Pond for beneficial reuse.

§ 257.73(c)(1)(iv): The name and size in acres of the watershed where the CCR unit is located.

The entire Primary Ash Pond and most of the Newton Power Station are located in the Weather Creek Watershed with a 12-digit Hydrologic Unit Code (HUC) of 051201140504 and a drainage area of 31,573 acres. The other portion of the Newton Power Station is located in the Newton Lake Watershed with a 12-digit Hydrologic Unit Code (HUC) of 051201140503 and a drainage area of 967 acres (USGS, 2016).

§ 257.73(c)(1)(v): A description of the physical and engineering properties of the foundation and abutment materials on which the CCR unit is constructed.

The foundation materials consist of upper clay and lower clay. The physical characteristics properties of the upper clay layer are described as lean clay, fat clay, clayey sand, fat clay with sand, lean clay with sand, silty sand, silty clay, silty clay with sand, sandy lean clay. The upper clay soils exhibit a stiff to hard consistency. The physical characteristics of the lower clay layer are described as glacial till consisting of sandy lean clay, silty sand, clayey silt with sand, silty clay with sand, well graded sand with silt, lean clay, fat clay, clayey sand, silty clay, lean clay with sand, clayey sand with silt, and fat clay with sand. The consistency of the lower clay is very stiff to hard. A summary of the available engineering properties of the foundation materials is presented in **Table 1** below. The engineering properties are based on previous geotechnical explorations and laboratory testing.

Table 1. Summary of Foundation Material Engineering Properties

Material	Unit Weight (pcf)	Effective (drained) Shear Strength Parameters		Total (undrained) Shear Strength Parameters	
		Effective Friction Angle ϕ′ (deg)	Effective Cohesion c′ (psf)	S_u/σ'_c	Minimum C_u (psf)
Upper Clay	130	29	0	0.40 ($\sigma'_c \geq 2,000$ psf) 0.63 ($\sigma'_c < 2,000$ psf)	-
Lower Clay	130	33	3,700	-	5,000

The Primary Ash Pond is an enclosed impoundment with embankments and does not have abutments.

§ 257.73(c)(1)(vi): A statement of the type, size, range, and physical and engineering properties of the materials used in constructing each zone or stage of the CCR unit; the method of site preparation and construction of each zone of the CCR unit; and the approximate dates of construction of each successive stage of construction of the CCR unit.

Physical properties for the embankment are described as lean clay, lean clay with sand, silty clay, silty clay with sand, sandy lean clay, fat clay, fat clay with gravel and sand, fat clay with sand and silt, fat clay with sand, and clayey silt. An available summary of the engineering properties of the Primary Ash Pond embankment is presented in **Table 2** below. The engineering properties are based on previous geotechnical explorations and laboratory testing.

Table 2. Summary of Construction Material Engineering Properties

Material	Unit Weight (pcf)	Drained Strength		Undrained Strength
		Effective Friction Angle ϕ′ (deg)	Effective Cohesion c′ (psf)	S_u/σ'_c
Embankment Fill	130	31	0	0.41 ($\sigma'_c \geq 500$ psf) 1.39 ($\sigma'_c < 500$ psf)

The method of site preparation and construction of the Primary Ash Pond is not reasonably and readily available.

The approximate dates of construction of each successive stage of construction of the Primary Ash Pond are provided in **Table 3** below.

Table 3. Approximate dates of construction of each successive stage of construction.

Date	Event
1977	Construction of Primary Ash Pond
2009	Both Primary Ash Pond discharge pipes were lined with cured-in-place pipe (CIPP)
2014	Three areas along the interior berm were re-graded and covered with rip-rap

§ 257.73(c)(1)(vii): At a scale that details engineering structures and appurtenances relevant to the design, construction, operation, and maintenance of the CCR unit, detailed dimensional drawings of the CCR unit, including a plan view and cross sections of the length and width of the CCR unit, showing all zones, foundation improvements, drainage provisions, spillways, diversion ditches, outlets, instrument locations, and slope protection, in addition to the normal operating pool surface elevation and the maximum pool surface elevation following peak discharge from the inflow design flood, the expected maximum depth of CCR within the CCR surface impoundment, and any identifiable natural or manmade features that could adversely affect operation of the CCR unit due to malfunction or mis-operation.

Drawings that contain items pertaining to the requested information for the Primary Ash Pond are listed in **Table 4** below. Items marked as "Not Available" are items not found during a review of the reasonably and readily available record documentation.

Table 4. List of drawings containing items pertaining to the information requested in § 257.73(c)(1)(vii).

	Primary Ash Pond
Dimensional plan view (all zones)	S-69
Dimensional cross sections	S-70
Foundation Improvements	Not Applicable
Drainage Provisions	Not Applicable
Spillways and Outlets	S-50
Diversion Ditches	Not Applicable
Instrument Locations	Plate 2, Fig. No. 2A
Slope Protection	S-70
Normal Operating Pool Elevation	Not Available
Maximum Pool Elevation	Not Available
Approximate Maximum Depth of CCR in 2016	49 feet

All drawings referenced in **Table 4** above can be found in **Appendix B** and **Appendix C**.

Based on the review of the drawings listed above, no natural or manmade features that could adversely affect operation of the CCR unit due to malfunction or mis-operation were identified.

§ 257.73(c)(1)(viii): A description of the type, purpose, and location of existing instrumentation.

Existing instrumentation at the Primary Ash Pond include vibrating-wire and open-standpipe piezometers. The purpose of the piezometers is to measure the pore water pressures within and around the impoundment. Two (2) open-standpipe piezometers (B-2 and B-3) were installed in 2010 and the locations are presented on Plate 2 in **Appendix C**. Fourteen (14) vibrating-wire piezometers were installed in 2015 and the locations are presented on Figure 2A in **Appendix C**.

§ 257.73(c)(1)(ix): Area-capacity curves for the CCR unit.

Area-capacity curves for the Primary Ash Pond are not reasonably and readily available.

§ 257.73(c)(1)(x): A description of each spillway and diversion design features and capacities and calculations used in their determination.

The Primary Ash Pond contains two concrete, stop-log weir box structures that discharge to the Secondary Pond. Weir box 1-A is located at the bottom of the embankment and is connected to the lower 30-inch diameter (dia.) cured-in-place pipe (CIPP). Weir Box 1-B is located approximately halfway up the embankment is connected to the upper 30-inch dia. CIPP. Both discharge pipes were originally 30-inch dia. corrugated metal pipe (CMP) and were lined in 2008 (see section § 257.73(c)(1)(xii) below for further information). The lower discharge pipe from weir box 1A passes through the embankment between the Primary Ash Pond and Secondary Pond. The upper discharge pipe from weir box 1B connects to the lower discharge pipe within the embankment. In 2016, the discharge capacity of the Primary Ash Pond was evaluated using HydroCAD 10 software modeling a 1,000-year, 24-hour rainfall event. The results of the HydroCAD 10 analysis are presented below in **Table 5**.

Table 5. Results of HydroCAD 10 analyses

	Primary Ash Pond
Approximate Minimum Berm Elevation[1] (ft)	552.7
Approximate Emergency Spillway Elevation[1] (ft)	Not Applicable
Starting Pool Elevation[1] (ft)	534.0
Peak Elevation[1] (ft)	534.9
Time to Peak (hr)	17.0
Surface Area (ac)	169.0
Storage[2] (ac-ft)	159.4

Note: 1. Elevations are based on NAVD88 datum
2. Storage given is from Starting Pool Elevation to Peak Elevation.

§ 257.73(c)(1)(xi): The construction specifications and provisions for surveillance, maintenance, and repair of the CCR unit.

The construction specifications for the Primary Ash Pond are not reasonably and readily available.

The provisions for surveillance, maintenance, and repair of the Primary Ash Pond are located in *Operation and Maintenance Manual for Primary and Secondary Ash Ponds* (presented in **Appendix D**).

The operations and maintenance plan for the Primary Ash Pond is currently being revised by Illinois Power Generating Company. This section will be updated when the new operations and maintenance plan is available.

§ 257.73(c)(1)(xii): Any record or knowledge of structural instability of the CCR unit.

In September, 2008, a sinkhole was observed over the Primary Ash Pond discharge pipes. After performing a video inspection, it is believed that an open joint in the primary 30-inch dia. CMP discharge pipe allowed for soil to enter the discharge pipe and cause an internal void in the embankment. The sinkhole was backfilled and compacted with soil and a cured-in-place pipe (CIPP) was installed in both the upper and lower discharge pipes to prevent further internal erosion to the embankment. Following completion of the discharge pipe modification, grout was injected at several locations within the sinkhole to ensure any remaining voids were filled surrounding the discharge pipes. Information about this event can be found in the letter presented in **Appendix E**.

There is no record or knowledge of any other structural instability of the Primary Ash Pond at Newton Power Station.

LIMITATIONS

The signature of AECOM's authorized representative on this document represents that to the best of AECOM’s knowledge, information and belief in the exercise of its professional judgment, it is AECOM’s professional opinion that the aforementioned information is accurate as of the date of such signature. Any recommendation, opinion or decisions by AECOM are made on the basis of AECOM's experience, qualifications and professional judgment and are not to be construed as warranties or guaranties. In addition, opinions relating to environmental, geologic, and geotechnical conditions or other estimates are based on available data and that actual conditions may vary from those encountered at the times and locations where data are obtained, despite the use of due care.

Sincerely,

Claudia Prado

Claudia Prado	Victor Modeer, P.E., D.GE
Project Manager	Senior Project Manager

REFERENCES

United States Environmental Protection Agency (USEPA). (2015). *Hazardous and Solid Waste Management System; Disposal of Coal Combustion Residuals From Electric Utilities; Final Rule.* 40 CFR Parts 257 and 261, 80 Fed. Reg. 21302, 21380 April 17, 2015.

United States Geological Survey (USGS). (2016). The National Map Viewer. http://viewer.nationalmap.gov/viewer/. USGS data first accessed in March of 2016.

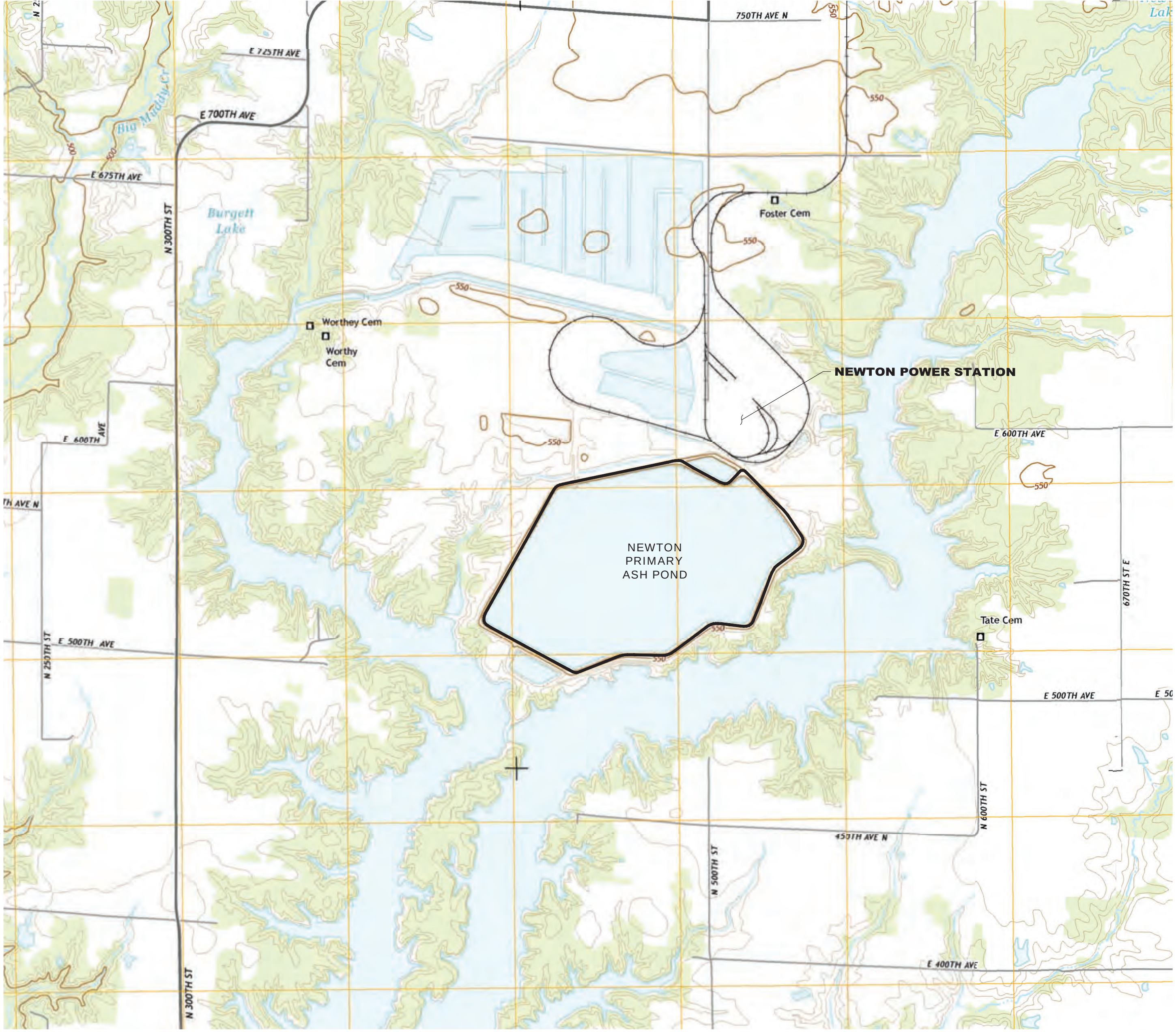
APPENDICES

Appendix A: History of Construction Vicinity Map
Appendix B: Newton Power Station Drawings
Appendix C: Newton Primary Ash Pond Boring and Piezometer Locations
Appendix D: Operation and Maintenance Manual for Primary and Secondary Ash Ponds
Appendix E: Newton Power Plant Site Visit Report 9-12-08, Hanson (2008)

Appendix A: History of Construction Vicinity Map

NANAK, MATT, 8/24/2016 5:35 PM

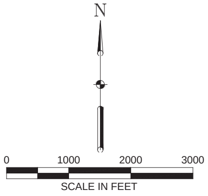
AECOM DRAWING PATH: P:\Projects\Geotech\60428794_DynegyCCR\13_Construction History\04 Technical Production\9_Newton\References\Vicinity Location Map References\Figures\C-01 History of Construction Vicinity Map (Newton)_ZJF.dwg



LEGEND

▭ CCR UNITS

SOURCE:
MAP PROVIDED FROM ELECTRONIC USGS DIGITAL RASTER GRAPHIC 7.5 MINUTE TOPOGRAPHIC MAP OF NEWTON, ILLINOIS AND LATONA, ILLINOIS, REVISED 2015.



AECOM
1001 Highlands Plaza Drive, Suite 300
St. Louis, Mo. 63110
314 429-0100 (phone)
314-429-0462 (fax)

ILLINOIS POWER GENERATING COMPANY
6725 North 500th St.,
Newton, IL 62448

HISTORY OF CONSTRUCTION

NEWTON POWER STATION
NEWTON, ILLINOIS

ISSUED FOR BIDDING ________ DATE BY

ISSUED FOR CONSTRUCTION ________ DATE BY

REVISIONS

NO.	DESCRIPTION	DATE
△		
△		
△		
△		
△		

AECOM PROJECT NO:	60489731
DRAWN BY:	DJD
DESIGNED BY:	DJD
CHECKED BY:	MN
DATE CREATED:	2016-04-13
PLOT DATE:	
SCALE:	1" = 1000'
ACAD VER:	2014

SHEET TITLE

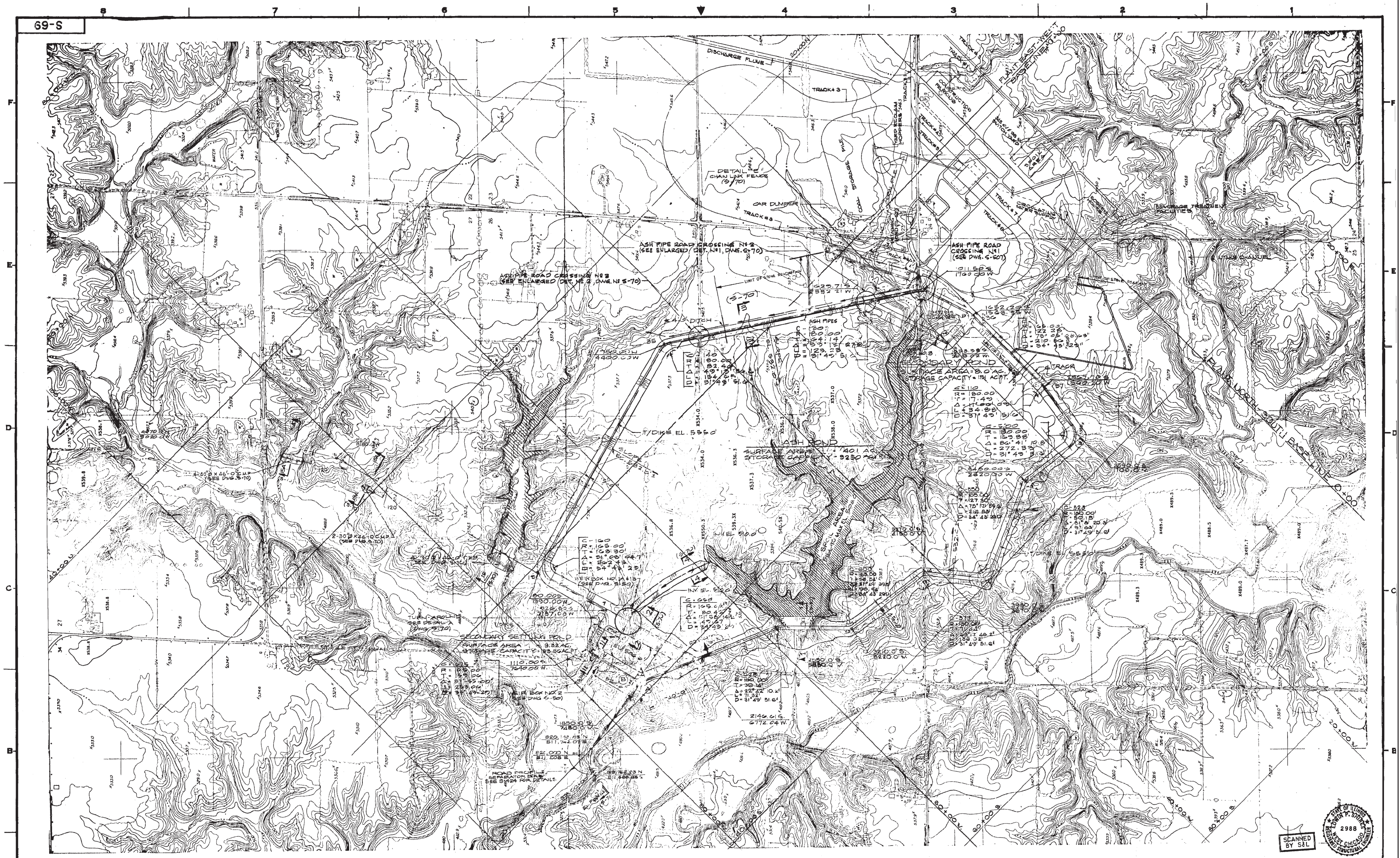
HISTORY OF CONSTRUCTION VICINITY MAP

01

Appendix B: Newton Power Station Drawings

1. “Ash Pond & SO_2 Disposal Pond”, Drawing No. S-69, Revision N, 29 July, 1994, Sargent & Lundy Engineers.
2. “Ash Pond Dike, Profile, Details, & Sections”, Drawing No. S-70, Revision M, 8 April, 1994, Sargent & Lundy Engineers.
3. “Weir Box Structures at Primary and Secondary Settling Ponds”, Drawing No. S-50, Revision K, 25 March, 1994, Sargent & Lundy Engineers.

69-S



POINT NO.	SIDE	CURVE NO.	R	T	Δ	L	D
8	ASH POND		100'	52.87'	49°43' 13.6"	86.78	57°17' 45.60"
8	SECONDARY ASH POND		65'	140.29'	130°16' 46.4"	147.80	88°08' 51.69"
21	LAKESIDE (A)		165'	49.55'	33°25' 06.4"	96.27	34°43' 29.00"
21	LAKESIDE (B)		65'	70.49'	94°36' 00.0"	107.32	88°08' 51.69"
36	ASH POND (A)		57.5'	57.50	90°00' 00.0"	90.27	99°38' 41.53"
36	SECONDARY (B) POND		57.5	77.59	106°54' 52.35"	107.24	99°38' 41.53"
39	SECONDARY POND		57.5	161.37	140°46' 29.17"	141.21	99°58' 41.53"

PLANT NORTH

NORTH

NOTES

7. THE WATER LEVEL IN ASH POND SHALL BE MAINTAINED AT AN ELEVATION 10'-0" ABOVE THE SEDIMENT LEVEL FOR ENVIRONMENTAL PURPOSES.

NOTES

1. FOR GENERAL NOTES SEE DWG. S-14.
2. ALL WORK SHOWN IN THIS DRAWING SHALL BE DONE BY SUPERSTRUCTURE CONTRACTOR IN ACCORDANCE WITH JOB SPEC. A-3022.
3. ALL EXTERIOR SIDE SLOPES OF DIKE BELOW ELEV. 510.0' THAT IS TO BE CONSTRUCTED BEFORE LAKE FILLING. SHALL BE PROVIDED WITH 24" STONE RIPRAP ON 24" SAND AND GRAVEL FILTER BEDDING AS SHOWN ON DWG. S-70. AND ALL DIKE CONSTRUCTION SHALL BE DONE IN ACCORDANCE WITH JOB SPEC. A-3017 AND A-3022.
4. ALL DIKE TOPS AND SIDE SLOPES AND ALL EXTERNAL DITCHES SHALL BE PROVIDED WITH 4" TOPSOIL AND SEEDED IN ACCORDANCE WITH JOB SPEC. A-3017 AND A-3022.
5. EXISTING LOW AREAS SHALL BE FILLED WITH SPOILMATERIAL AS REQUIRED FOR SPOIL DISPOSAL SPOILS SHALL BE PLACED IN LAYERS AND GRADED PROPERLY FOR DRAINAGE.
6. REMOVED "HOLD" FROM SO_2 POND AREAS FOR CLEARING. SLOPE STAKING & CROSS- SECTIONING ONLY.

REFERENCE DRAWINGS

S-19	SITE CONTOURS AND DEVELOPMENT PLAN SHEET 4.
S-39	GRADING AND DRAINAGE PLAN, PLANT AREA SHEET 2.
S-40	GRADING AND DRAINAGE PLAN, PLANT AREA SHEET 3.
S-50	WEIR BOX STRUCTURES AT PRIMARY AND SECONDARY SETTLING PONDS.
S-70	ASH POND DIKE PROFILE DETAILS & SECTION
S-507	GRADING & DRAINAGE PLAN- PLANT AREA- SHT7.

Drawing Release Record

Rev	Date	Init	Description
N	07-29-94	TM	SCANNED BY S&L
A	11-29-74	CRB	[illegible]
B	2-10-75	[illegible]	REMOVED SO_2 [illegible] FOR [illegible]
C			HOLD [illegible] POND DIKE & REMOVE [illegible]
D	7-15-75	[illegible]	[illegible]
E	12-21-75	CRB	REMOVED HOLD OF SO_2 POND [illegible]
F	7-12-76	CRB	[illegible]
G	9-13-76	CRB	ADD WEIR BOX [illegible] & REMOVE HOLD ON WEIR BOX # 1 & [illegible]
	--	--	REV. ROAD [illegible]
H	1-24-77	CRB	ADD [illegible]
J	10-21-77	SPL	SHOWN LIMIT OF STONE RIPRAP
K	11-8-79	[illegible]	REV. STORAGE CAPACITIES CORRESPONDING TO [illegible]
L	7-8-80	RJJ	[illegible] REVISION
M	2-20-81	[illegible]	SENT TO CLIENT

ASH POND & SO_2
DISPOSAL POND
NEWTON POWER STATION UNIT 1
CENTRAL ILL PUBLIC SERVICE CO.
NEWTON, ILLINOIS

SCALE 1" = 400'-0" & U.N.
DRAWN B. SANCHEZ 8-6-74
CHECKED C. R. Bhattacharya 8-6-74
ENGINEER A. J. Skala 8-6-74
APPROVED [illegible] 8-6-74
JOB NO. 1486-03 1486-15 [illegible]

SARGENT & LUNDY
ENGINEERS
CHICAGO

DRAWING NO.
S-69

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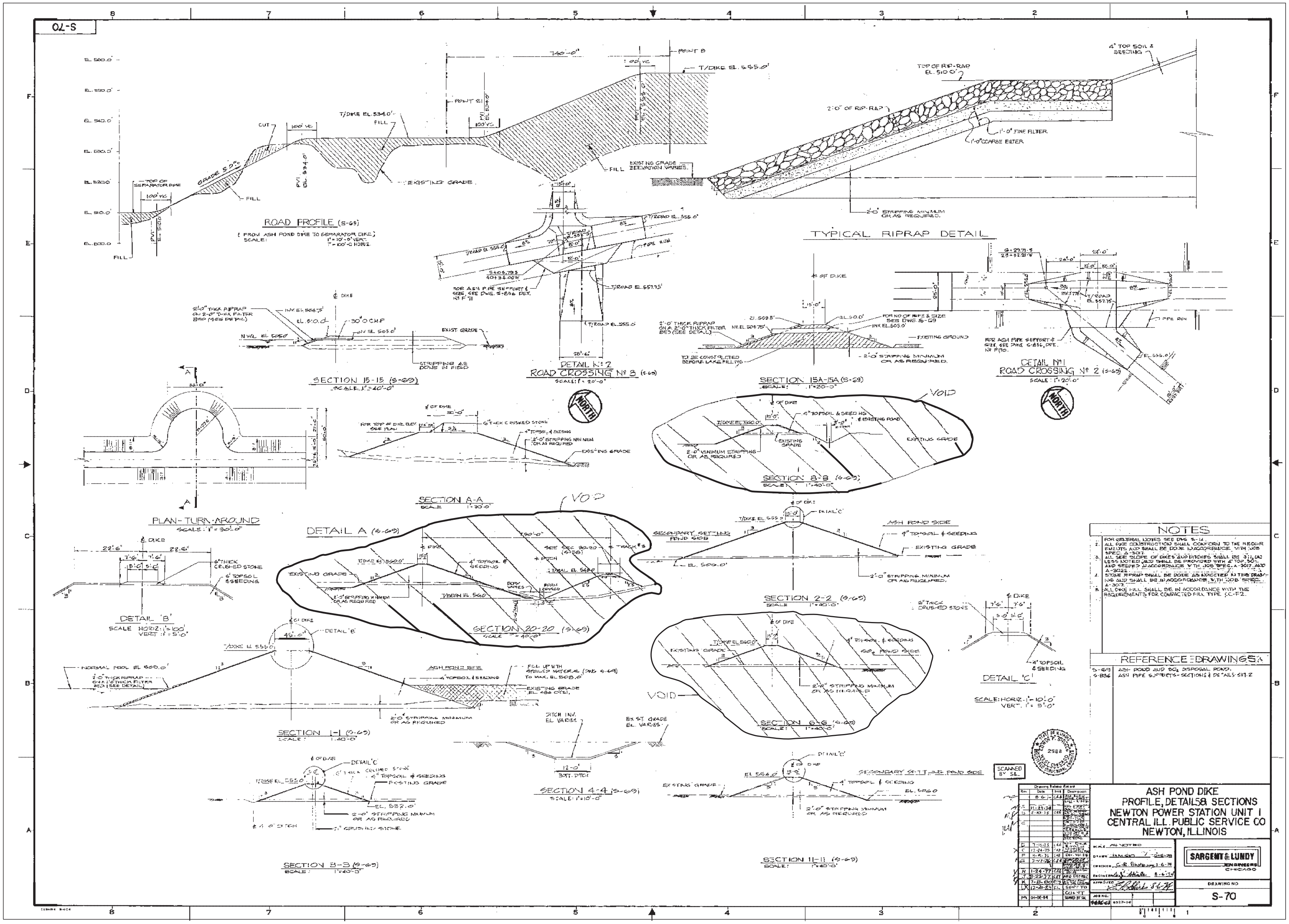


NOTES

1. FOR GENERAL NOTES SEE DWG. S-14.
2. ALL DIKE CONSTRUCTION SHALL CONFORM TO THE REQUIREMENTS AND SHALL BE DONE IN ACCORDANCE WITH JOB SPEC. A-3017.
3. ALL SIDE SLOPE OF DIKES AND DITCHES SHALL BE 3:1, UNLESS NOTED AND SHALL BE PROVIDED WITH 4" TOP SOIL AND SEEDED IN ACCORDANCE WITH JOB SPEC. A-3017 AND A-3022.
4. STONE RIPRAP SHALL BE DONE AS INDICATED IN THIS DRAWING AND SHALL BE IN ACCORDANCE WITH JOB SPEC. A-3017.
5. ALL DIKE FILL SHALL BE IN ACCORDANCE WITH THE REQUIREMENTS FOR COMPACTED FILL TYPE CC-F2.

REFERENCE DRAWINGS

S-69	ASH POND AND SO2 DISPOSAL POND.
S-836	ASH PIPE SUPPORTS - SECTIONS & DETAILS - SHT. 2

Drawing Release Record

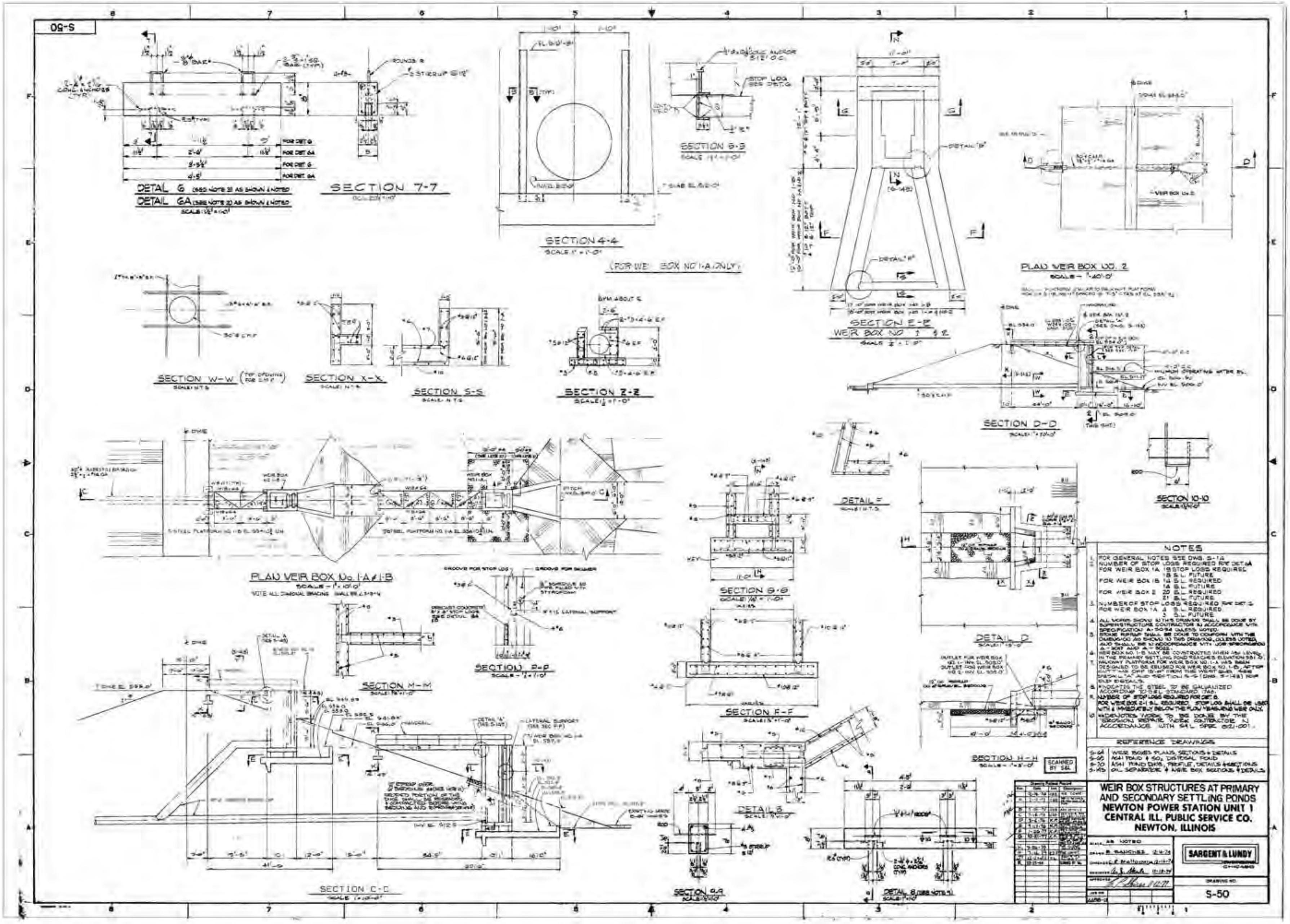
Rev	Date	Init	Description
	8-6-74	CLB	[illegible]
A	11-25-74		[illegible]
B	2-10-75	CEB	[illegible]
C			[illegible]
D	7-15-75	CEB	[illegible]
E	12-24-75	CEB	[illegible]
F	4-15-76	CEB	[illegible]
G	7-27-76	CEB	[illegible]
H	1-24-77	CEB	[illegible]
J	9-22-77	EAT	ADD DETAIL
K	7-8-80	CJ	[illegible]
LX	12-20-83	EL	SENT TO CLIENT
M	01-06-94		SCANNED BY S&L

ASH POND DIKE
PROFILE, DETAILS & SECTIONS
NEWTON POWER STATION UNIT 1
CENTRAL ILL. PUBLIC SERVICE CO
NEWTON, ILLINOIS

SCALE AS NOTED
DRAWN [illegible] 8-6-74
CHECKED C.R. Bhatia 8-6-74
ENGINEER [illegible] 8-6-74
APPROVED [illegible] 8-6-74
JOB NO. 4527-00

SARGENT & LUNDY ENGINEERS CHICAGO

DRAWING NO
S-70



NOTES

1. FOR GENERAL NOTES SEE DWG. S-1A
2. NUMBER OF STOP LOGS REQUIRED FOR DET. 6A
   FOR WEIR BOX 1A 19 STOP LOGS REQUIRED
   18 S.L. FUTURE
   FOR WEIR BOX 1B 14 S.L. REQUIRED
   14 S.L. FUTURE
   FOR WEIR BOX 2 20 S.L. REQUIRED
   21 S.L. FUTURE
3. NUMBER OF STOP LOGS REQUIRED FOR DET. G
   FOR WEIR BOX 1A 4 S.L. REQUIRED
   3 S.L. FUTURE
4. ALL WORK SHOWN ON THIS DRAWING SHALL BE DONE BY SUPERSTRUCTURE CONTRACTOR IN ACCORDANCE WITH SPECIFICATION A-5094 UNLESS NOTED.
5. STONE RIPRAP SHALL BE DONE TO CONFORM WITH THE DIMENSIONS AS SHOWN ON THIS DRAWING, UNLESS NOTED, AND SHALL BE IN ACCORDANCE WITH JOB SPECIFICATION A-3017 AND A-3022.
6. WEIR BOX NO. 1-B MAY BE CONSTRUCTED WHEN ASH LEVEL IN THE PRIMARY SETTLING POND REACHES ELEVATION 531.0.
7. WALKWAY PLATFORM FOR WEIR BOX NO. 1-A HAS BEEN DESIGNED TO BE REUSED FOR WEIR BOX NO. 1-B, AFTER CUTTING OFF 15'-0" FROM THE WEST END. SEE DETAIL "A" AND SECTION S-S (DWG. S-148) FOR END DETAILS.
8. INDICATES THE STEEL TO BE GALVANIZED ACCORDING TO S&L STANDARD 1746.
9. NUMBER OF STOP LOGS REQUIRED FOR DET. B.
   FOR WEIR BOX 2-1 S.L. REQUIRED. STOP LOG SHALL BE USED WITH & IMMEDIATELY BELOW THE FLOW MEASURING WEIR ONLY.
10. INDENOTES WORK TO BE DONE BY THE EROSION REPAIR WORK CONTRACTOR IN ACCORDANCE WITH S&L SPEC. 6121-001.

REFERENCE DRAWINGS

S-64	WEIR BOXES PLANS, SECTIONS & DETAILS
S-65	ASH POND & SO₂ DISPOSAL POND
S-70	ASH POND DIKES, PROFILE, DETAILS & SECTIONS
S-145	OIL SEPARATOR & WEIR BOX SECTIONS & DETAILS

WEIR BOX STRUCTURES AT PRIMARY
AND SECONDARY SETTLING PONDS
NEWTON POWER STATION UNIT 1
CENTRAL ILL. PUBLIC SERVICE CO.
NEWTON, ILLINOIS

SCALE AS NOTED
DRAWN B. SANCHEZ 12-16-74
CHECKED C.F. Mattoomian 12-16-74
REVIEWED A. J. Mode 12-18-74
APPROVED 1-12-77

SARGENT & LUNDY
ENGINEERS
CHICAGO

DRAWING NO.
S-50

Appendix C: Newton Primary Ash Pond Boring and Piezometer Locations

NOTES

1. Plan adapted from an aerial photograph courtesy of Google Earth.

LEGEND

- ● Boring Location
- ▬ Slope Stability Cross Section

0 400 800 1,600

SCALE IN FEET

N

Drawn By: SLC	Ck'd By:	App'vd By:
Date: 11-10-10	Date: 12/21/10	Date: 1/4/11

GEOTECHNOLOGY INC
FROM THE GROUND UP

Newton Power Station
Newton, Illinois

AERIAL PHOTOGRAPH OF SITE AND BORING LOCATIONS

Project Number J017150.01	PLATE 2

▨ XXX-X###

EXPLORATION METHOD (B=BORING, C=CPT, P=PIEZOMETER)

ID NUMBER

STATION ABBREVIATION

SOURCE:
MAP PROVIDED BY GOOGLE EARTH PRO 2015

LEGEND

▨ PIEZOMETER LOCATION

▬ ▪ ▬ CCR UNIT BERM ALIGNMENT

0 600
APPROXIMATE SCALE FEET

Illinois Power Generating Company

PROJECT NO.
60440378

AECOM

DRN. BY: djd October 2015
DSGN. BY: eg
CHKD. BY: eg

Newton Primary Ash Pond
Piezometer Locations

FIG. NO.
2A

File: P:\PROJECTS\GEOTECH\60428794_DYNEGYCCR\04TASKS\00 PROGRAM TASKS\1.0 TASK 1 INITIAL UNIT ASSESSMENT\CCR FACT SHEETS\SITE MAPS\FIGURE 2A PIEZOMETER LOCATION PLAN (NEWTON PRIMARY ASH POND).DWG Last edited: NOV. 04, 15 @ 1:32 p.m. by: david_deguire

Appendix D: Operation and Maintenance Manual for Primary and Secondary Ash Ponds

Newton Power Station

Operational Procedure

x-xxx-xxxx--xxx

Operation & Maintenance Manual for Primary and Secondary Ash Ponds

Effective Date: xx/xx/xxxx

Reason for Change: New Procedure

Approved By: *x* Date: xx/xx/xxxx

x
Lindel Wenthe

Responsible Department: Newton Power Station, Technical Services Department

- ☐ **This entire document shall be in the field during procedure performance.**
- ☐ **The following portions of this procedure shall be in the field during procedure performance: ____________________**
- ☐ **__________ from this procedure shall be in the field during procedure performance.**
- ☐ **No part of this procedure is required to be in the field during procedure performance.**

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Section **Page Number**

1.0 Purpose

1.1 This procedure is intended to ensure the safe and environmentally responsible operation and use of all water impoundment and levee structures at Newton Power Station facility. The primary purpose of Newton's Primary, Secondary Ash Ponds, and SO2 Chemical Pond are for the storage of fly ash and treatment of fly ash sluice water to meet NPDES Permit Conditions. This procedure then assures:

1.1.1 The embankment structures and flow regulating structures are properly operated and maintained.

1.1.2 Inspections of these structures are conducted.

1.1.3 A maintenance program will be performed.

1.1.4 Communication takes place with the Dam Safety Staff regarding the structures' condition and operation.

2.0 Scope

2.1 This procedure applies to all onsite personnel and the Dam Safety Group staff.

3.0 Responsibilities

3.1 On-site Technical Services – Conducts ash pond and levee embankment and structure observations and completes the inspections, reporting any undesirable conditions to the Supervising Engineer, Dam Safety.

3.2 On-site personnel – Operates the facilities as described in this Operational Procedure. Reports any conditions noted during routine activities to the shift supervisor. Coordinates scheduling of maintenance as required to maintain proper operations of the ash pond facility.

3.3 Shift Supervisor (SS) - Calls Technical Service personnel when structure concerns are reported. Make entries into the shift log book indicating the concern and actions taken.

3.4 Supervising Engineer, Dam Safety - Conducts annual detailed dam safety inspections and provides a report with findings and recommendations.

4.0 Historical Information

4.1 Construction began in 1972 and concluded in 1982. Unit 1 was placed in service in 1977; Unit 2 went into commercial operation in 1982.

5.0 Flow Regulating Structures

5.1 Embankments

- Primary Ash Pond (Bottom Ash)
  Top of ash pond berm elevation was designed at Elevation 555.00'. Therefore, normal high pool elevation is 450.00. This allows for 2.9 feet of storage depth over the top of the ash pond outlet structure; or approximately 116 acre-ft storage or 37,850,000 gallons (45% of 89 acres times 2.9' deep).

- Secondary Ash Pond (Bottom Ash)

5.2 Structures

- Primary Ash Pond Outlet Structures - The water level in the pond is regulated by stop logs in the concrete outlet structures on the south side of the Primary Ash pond. Plans showing the outlet structures and walkways are on file. The main pond outlet structure shall be checked regularly (at least weekly or more often if there are excessive rain events) to ensure proper pond discharge. Elevation of the top of the main structure is 537.00'. Elevation of the walkway is 537.00'. Normal depth of flow over the drop structure is 3 to 4 inches during non-rainfall discharge. A 30-inch diameter CMP exits the outlet structure directly to the secondary settling pond.
- Secondary Ash Pond Outlet Structures - The water level in the pond is regulated by the pond outlet structures on the south side of the Secondary Ash pond. Plans showing the outlet structures and walkways are on file. The Secondary Ash Pond outlet structure shall be checked regularly (at least weekly or more often if there are excessive rain events) to ensure proper pond discharge. Elevation of the top of the structure is 534.00'. Elevation of the walkway is 534.00'. Minimum operating water level elevation is 516.50'. Normal depth of flow over the drop structure is 3 to 4 inches during non-rainfall discharge. A 30-inch diameter CMP exits the outlet structure directly to Newton Lake.
- Primary Ash Pond Process Water Discharge Pipe – This culvert regulates the level of water in the Primary Ash Pond. There are two possible inlets in the Primary ash pond outlet structures. Inlet Flowline elevations of the Primary Ash Pond pipe are 512.50' and 536.00'. Both inlets are connected into the same 30" CMP roughly halfway through the embankment. The outlet elevation of these combined pipes is 508.00'. These combined pipes failed once in the past at the point of connection of the top pipe into the main pipe and caused the embankment to erode from the inside and

caused a sinkhole to develop. The solution that was devised to deal with the problem was to line the entire 30” CMP with a cured in place liner. This rehabilitated the corrugated metal pipe and restored the interior integrity of the outlet pipe. The embankment was then filled with clam material and returned to service.

- Secondary Ash Pond Bottom Ash/Process Water Culvert Pipe – This 30” corrugated metal culvert pipe regulates the level of water in the Secondary Ash Pond. This pipe was also lined with a cured in-place liner. Inlet flowline elevation of the Secondary Ash Pond outlet pipe is 506.00’. The outlet elevation of this pipe is 505.00’.

6.0 Operations Requirements

Normal Operation - Plant personnel shall monitor the level of all ash pond basins within the perimeter ash pond berm on a daily basis. If levels within any of the basins exceed the prescribed maximum levels, action shall be taken immediately to remedy the situation.

Normal Operating Levels	
Primary Ash Pond Outlet	508’
Secondary Ash Pond Outlet Structure	505’
Primary Ash Pond Water Level	536’
Secondary Ash Pond Water Level	516.5’

Emergency Conditions – If a condition arises where there is a possibility of an embankment failure, then the following procedures will be followed:

1. Notify the Supervising Engineer Dam Safety immediately.
2. The pond level will be lowered by portable pumps. Monitor the embankment for changed conditions.
3. Initiate Emergency Action Plan

7.0 Maintenance Requirements

7.1 Maintenance Program - The plant’s impoundment and flood prevention structures shall be inspected and maintained in a manner to ensure safe and environmentally responsible operations. A regular maintenance program shall be performed and shall consist of the following inspection items:

1. Earth embankments: Walk the crest, side slopes, and downstream toe of the dam concentrating on surface erosion, seepage, cracks, settlement, slumps, slides, and animal burrows. Frequency of inspection: Quarterly.

2. Vegetation: Grass should be a thick vigorous growth to stabilize the earth embankment soils and prevent erosion form occurring. Note the height of the grass; if greater than one foot a mowing of the area should be scheduled before the next inspection. There should be NO trees on the earth embankment and none within a minimum of 20 feet of the embankment toe or other structures. Frequency of inspection: Weekly.
3. Pond Outlet Structure: Check for any debris or other obstructions around the concrete inlet which may block or restrict the flow of water. Check for the development of any rusty areas on the concrete, and seepage, cracking, breaking, or spalling of concrete. Check for settlement or cracking in the walkway structure. Frequency of inspection: Monthly.
4. Outlet Pipe Slide Gate: Check the structure for development of any rusty areas on the concrete, and seepage, cracking, breaking, or spalling of concrete. Check the slide gate stem, grease the stem, and operate the slide gate through its full range of motion to ensure proper operation. Check for buildup of debris in the manhole. Frequency of inspection: Quarterly.
5. Pond/Levee Perimeter: Check the perimeter of the embankment and levee for a distance of at least 100 feet from the toe for signs of seepage or boils. Inspection frequency for levee will be determined by Dam Safety Engineer during flood events. Frequency of ash pond embankment inspection: Quarterly for ash pond embankment.
6. Special Inspections – Special inspections of ash pond berms shall be performed after earthquakes, floods, water level exceedance in the ponds, or heavy rainfall events. Inspection and report shall be equal to an annual inspection level of detail. Water level in the pond should be noted after a heavy rainfall. Dam Safety staff shall accompany plant personnel on special inspections. Frequency: As required.

8.0 Maintenance Logs

8.1 Plant personnel shall maintain an up-to-date log of operations (water levels, gate adjustments, inlet and outlet flows, serpentine channels, etc.), visual observations, unusual occurrences, and maintenance performed. The log book shall be reviewed during the Annual Engineering Inspection. Logs shall be kept for the life of the plant.

9.0 Contact Numbers

Plant Environmental Supervisor: David Heath / 618-783-0311
Plant Shift Supervisors Office: 217-783-0344

Plant Control Room: 217-783-0501 / 217-783-0502
Supervising Engineer Dam Safety: Steve Bluemner / 314-554-6298
Dam Safety Staff Contact: Dan Haarmann / 217-371-4853

10.0 References

10.1 AER - DSP-004, "Dam Safety Program for Non-Illinois Department of Natural Resources (non-IDNR) Regulated Facilities"

10.2 Drawings

Drawing Number	Sheet Name	Date
S-50	Weir Box Structures at Primary and Secondary Settling Ponds	12-16-74
S-69	Ash Pond and SO2 Disposal Pond	8-6-74
S-70	Ash Pond Dike Profile, Details & Sections	8-6-74
S-836	Ash Pipe Supports Sections and Details SHT #2	2-8-80

11.0 Records

	Record Type	Responsible Person	Retention Period	Location
11.1	Copies of weekly inspections	Plant Technical Services	Life of plant	Onsite Environmental Supervisor and Dam Safety Department office
11.2	Copies of Quarterly inspections	Plant Technical Services	Life of plant	Onsite Environmental Supervisor and Dam Safety Department office
11.3	Log Book	Plant Technical Services	Life of plant	Onsite Environmental Supervisor office

Appendix E: Newton Power Plant Site Visit Report 9-12-08, Hanson (2008)

HANSON

MEMORANDUM
(Form QAP 17.2.3, Rev. 2)

TO: Dan Whalen DATE: 9/15/08

FROM: John Jenkins

SUBJECT: Ameren Newton Power Plant
Site Visit Report 9-12-08

On Friday September 12, 2008, I made a site visit to Newton Power Station to observe a sinkhole that has developed on the ash pond dike. I was accompanied by Matt Frerking and Jim Marshall of Ameren.

The sinkhole has developed on the downstream crest of the dike between the primary (upper) and secondary (lower) ash ponds (see attached photos). The sinkhole was first observed the morning of September 12, 2008 after a heavy rain. The sinkhole is circular in shape with a diameter of approximately 12 ft. The depth to the bottom of the sinkhole is estimated to be 10 to 12 ft. The sinkhole has developed directly over the location where two discharge pipes between the primary and secondary ponds are joined (see attached Section C-C). The discharge pipes are 30 in. diameter corrugated metal pipes (CMP) installed in the late 1970's. There was no indication of ground movement in the form of settlement or bulging of the dike embankment outside the area of the sinkhole. The water level in the primary ash pond is approximately El. 536 and the water level in the secondary pond is maintained at minimum El. 516.5. There has been no significant fluctuation of the water levels in either pond for over 6 months. The top of the dike is at El. 555 and the top of the discharge pipe below the sinkhole location is approximately El. 514. Therefore, the depth below the ground surface to the top of the pipe at the sinkhole location is approximately 41 ft.

Based on the location of the sinkhole relative to the discharge pipes and considering the age of the metal pipes, it appears that the most likely cause of the sinkhole is due to loss of soil material through a hole or holes in the discharge pipes. In particular, the connection between the two pipes is suspect. The pipe discharges into the secondary pond below the water level and therefore there is no way to visually observe the discharge for soil deposits. If the cause of the sinkhole is due to loss of material through holes in the pipes, this process could have been occurring over several years. There is the possibility that there is a void or voids that extend from the ground surface to the discharge pipes, and it would be expected that the sinkhole would continue to develop over time. It is possible that additional settlement or sloughing of soil material on the downstream crest of the embankment in the immediate vicinity of the sinkhole will occur in the near future. However, considering the relatively low level of water in the primary ash pond relative to the top of the dike embankment, the dike should remain stable even if local failures in the upper portion of the dike occur.

It was agreed that the following actions be taken.

- The existing sinkhole should be filled with soil material to prevent further sloughing and expanding of the sides of the sinkhole. The material should be placed with a backhoe and compacted with the backhoe bucket. No mechanical compaction of the soil should be attempted. The top of the filled area should be crowned to prevent ponding in the area of the sinkhole, and the sinkhole area should be monitored daily for additional settlement or movement.
- The primary ash pond level should be lowered in order to allow the pipes to be dewatered and inspected by camera. Jim Marshall estimates that it may take more than a week to draw the water down to the required depth.
- Based on the results of the camera survey, a plan for repair of the discharge pipes will be developed. The repair plan may include slipform lining of the pipes and/or excavation to repair isolated areas.
- Due to the unknown extent of the sinkhole void and to the possibility of additional voids being present along the length of the discharge pipe, Hanson will evaluate alternative methods for investigating the presence of voids below the ground surface, including the use of ground penetrating radar.

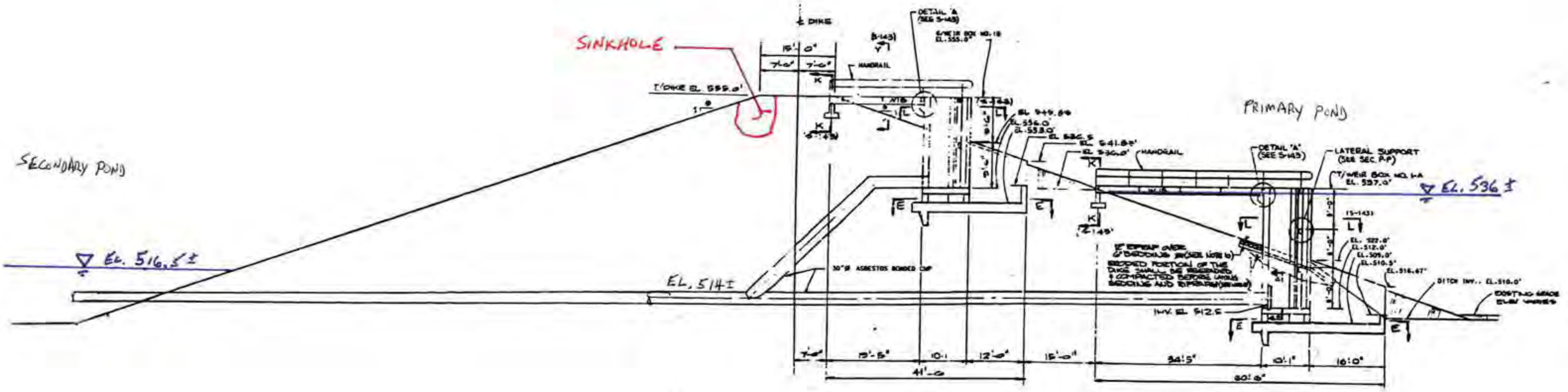
View of Sinkhole Looking Northwest Along Dike

View of Sinkhole Looking Southeast Along Dike

Close-Up of Sinkhole

View of Bottom of Sinkhole

View of Sinkhole Looking Southwest Towards the Secondary Pond and Lake



18" RIPRAP OVER 6" BEDDING (SEE NOTE 6) ERODED PORTION OF THE DIKE SHALL BE REGRADED & COMPACTED BEFORE LAYING BEDDING AND RIPRAP

SECTION C–C

SCALE: 1"=10'-0"

ATTACHMENT C

Newton Power Plant - Ash Pond's Chemical Constituents

In accordance with 35 I.A.C. 845.230(d)(2)(C), IPGC is submitting available/existing analyses of "the chemical constituents of all waste streams, chemical additives and sorbent materials entering or contained in" the CCR impoundment, Ash Pond.

A list of the chemical constituents' analyses contained in the CCR surface impoundment can be found in Appendix A. As determined through antidegradation studies, this list contains chemical constituents found in the surface free liquid and the subsurface free liquids. IPGC is also including a list of chemical additives, sorbent materials and waste streams that were submitted in the facility's NPDES permit applications to IEPA within the past ten years at a minimum and/or listed in the current NPDES permit (IL0001554) in Appendix B.

Appendix A: Chemical Constituents Contained in the Ash Pond

Pollutant	Units	Surface Free Liquids Average Concentration	Subsurface Free Liquids Average Concentration
Acidity (total)	mg/L	< 20.0	< 20.0
Alkalinity (total)	mg/L	98.3	327
Ammonia Nitrogen	mg/L	< 0.10	3.0
Antimony (dissolved)	mg/L	< 0.00031	0.00105
Antimony (total)	mg/L	< 0.00034	0.0079
Arsenic (dissolved)	mg/L	0.0021	0.0275
Arsenic (total)	mg/L	0.0023	0.0297
Barium (dissolved)	mg/L	0.246	0.191
Barium (total)	mg/L	0.27	0.62
Beryllium (dissolved)	mg/L	< 0.00050	< 0.001
Beryllium (total)	mg/L	< 0.00050	< 0.0011
Boron (dissolved)	mg/L	0.421	4.2
Boron (total)	mg/L	0.416	4.7
Cadmium (dissolved)	mg/L	< 0.00050	0.0007
Cadmium (total)	mg/L	< 0.00050	0.0008
Calcium (total recoverable)	mg/L	19.1	57.9
Chemical Oxygen Demand	mg/L	34.9	46.9
Chloride (total)	mg/L	10.9	19.2
Chromium (dissolved)	mg/L	0.0018	0.00070
Chromium (hexavalent)	mg/L	0.0016	0.0013
Chromium (total)	mg/L	0.002	0.007
Cobalt (dissolved)	mg/L	< 0.00011	0.001
Cobalt (total)	mg/L	< 0.00020	0.016
Copper (dissolved)	mg/L	0.0020	0.001
Copper (total)	mg/L	0.0026	0.0156
Cyanide (dissociable)	mg/L	< 0.010	0.4
Cyanide	mg/L	< 0.010	0.3
Fluoride	mg/L	0.65	0.44
Iron (dissolved)	mg/L	0.055	0.069
Iron (Ferric)	mg/L	0.08	2.89
Iron (Ferrous)	mg/L	< 0.12	< 0.4
Iron (total)	mg/L	0.142	3.1
Kjeldahl Nitrogen (total)	mg/L	1.1	4
Lead (dissolved)	mg/L	< 0.001	0.001
Lead (total)	mg/L	< 0.001	0.005
Lithium (total recoverable)	mg/L	< 0.010	0.028
Magnesium (total recoverable)	mg/L	5.46	2.8
Manganese (dissolved)	mg/L	0.0020	0.003
Manganese (total)	mg/L	0.0083	0.019
Mercury (dissolved)	mg/L	0.000044	0.0023
Mercury (total)	mg/L	0.000095	0.0033

Pollutant	Units	Surface Free Liquids Average Concentration	Subsurface Free Liquids Average Concentration
Molybdenum (dissolved)	mg/L	0.0145	0.267
Molybdenum (total)	mg/L	0.015	0.263
Nickel (dissolved) 200.8 WD	mg/L	< 0.00055	0.007
Nickel (dissolved) 6020 WD	mg/L	< 0.00057	0.007
Nickel (total)	mg/L	< 0.00077	0.0115
Nitrate as N	mg/L	< 0.10	0.09
Nitrite as N	mg/L	< 0.10	0.08
Oil & grease	mg/L	< 5.4	5.1
Oxidation/Reduction Potential	mg/L	-100	-276.7
pH*	SU	9.3	10.0
Phenols	mg/L	< 0.050	0.06
Phosphorus	mg/L	< 0.31	1.8
Potassium (dissolved)	mg/L	7.71	50.9
Potassium (total recoverable)	mg/L	7.7	52.8
Radium - 226	mg/L	0.99	0.63
Radium - 228	mg/L	0.87	1.03
Radium (total)	mg/L	1.87	1.66
Selenium (total)	mg/L	0.0042	0.038
Silica	mg/L	1.75	50.0
Silver (dissolved)	mg/L	< 0.00050	< 0.0009
Silver (total)	mg/L	< 0.00050	0.0009
Sodium (total recoverable)	mg/L	64.6	1365
Specific Conductance	mg/L	430.5	5827
Sulfate	mg/L	117	2554
Sulfide (total)	mg/L	0.051	1.5
Thallium (dissolved)	mg/L	< 0.001	< 0.002
Thallium (total)	mg/L	< 0.001	0.002
Total dissolved solids	mg/L	272	4700
Total Organic Carbon	mg/L	6.5	7.6
Total suspended solids	mg/L	37.9	92.6
Zinc (dissolved)	mg/L	< 0.010	0.013
Zinc (total)	mg/L	< 0.010	0.032

*Used https://calstormcompliance.com/ph-averaging-tool

Appendix B: List of Chemical Additives, Waste Streams and Sorbent Materials

Chemical Additives
Nalco PC-191 or equivalent (Anti-scalant)
Nalco PC-56 or equivalent (Biocide)
Ondeo-Nalco CA-250 or equivalent (Cationic Polymer)
General Chemical Hyper+Ion-1090 or equivalent (Aluminum Chlorohydrate)
Aluminum Chlorohydrate
Sodium Hydroxide (50%)
Sulfuric Acid (93%)
GE Betz Spectrus OX1200 or equivalent (Granular Bromine)
Anhydrous Ammonia
Dust suppression agents for coal
Hydrated Lime
Sodium Bicarbonate
Coal Dust Suppression Products*
Calcium Bromide for mercury control*

* Only a very small percentage of these chemicals would enter the ash pond. A high majority of the product would be consumed in the combustion process. Varying products may be used.

Waste Streams and Sorbent Materials*
Bottom & fly ash sluice water
Wastewater sumps
Water treatment filter backwash
Reverse osmosis reject water
Mixed bed waste water
Air heater wash water
Boiler blowdown
Sewage treatment plant #2 discharge
Coal pile runoff
Stormwater runoff
SCR module wastewater
Non-Chemical Metal Cleaning Wastewater

*No sorbent materials

Safety Data Sheet

Section 1
Identification of the Substance and of the Supplier

1.1 Product Identifier

Product Name/Identification:	ASTM Bottom Ash
Synonyms:	Ash; Ashes; Ash residues; Ashes, residues, bottom; Bottom ash; Bottom ash residues; Coal Fly Ash; Pozzolan; Waste solids.
Formula:	UVCB Substance

1.2 Relevant Identified Uses of the Substance or Mixture and Uses Advices Against

Relevant Identified Uses:	Component of wallboard, concrete, roofing material, bricks, cement kiln feed.
Uses Advised Against:	None known.

1.3 Details of the Supplier of the SDS

Manufacturer/Supplier:	Dynegy, Inc.
Street Address:	601 Travis Street, Suite 1400
City, State and Zip Code:	Houston, TX 77002
Customer Service Telephone:	800-633-4704

Section 2
Hazards Identification

2.1 Classification of the Substance

GHS Classification(s) according to OSHA Hazard Communication Standard (29 CFR 1910.1200):

- Eye Irritant, Category 2A
- STOT-SE, Category 3 (Respiratory Irritation)
- Carcinogen, Category 1A
- STOT-RE, Category 1 (Lungs)
- Toxic to Reproduction, Category 2

2.2 Label Elements

Labelling according to 29 CFR 1910.1200 Appendices A, B and C*	
Hazard Pictogram(s):	
Signal word:	**DANGER**
Hazard Statement(s):	*Causes serious eye irritation.* *May cause respiratory irritation.* *May cause damage to lungs after repeated/prolonged exposure via inhalation.* *May cause cancer of the lung.* *Suspected of damaging fertility or the unborn child.*
Precautionary Statement(s):	*Obtain special instructions before use.* *Do not handle until all safety precautions have been read and understood.* *Avoid breathing dust.* *Wash thoroughly after handling.* *Do not eat drink or smoke when using this product.* *Wear protective gloves/protective clothing/eye protection/face protection.* *Use outdoors or in a well-ventilated area.* *If exposed or concerned: Get medical advice/attention.* *Store in a secure area.* *Dispose of product in accordance with local/national regulations.*

** Fly ash and other coal combustion products (CCPs) are UVCB substances (unknown or variable composition or biological). Various CCPs, noted as ashes/ash residuals; Ashes, residues, bottom; Bottom ash; Bottom ash residues; Waste solids, ashes under TSCA are defined as: "The residuum from the burning of a combination of carbonaceous materials. The following elements may be present as oxides: aluminum, calcium, iron, magnesium, nickel, phosphorus, potassium, silicon, sulfur, titanium, and vanadium." Ashes including fly ash and fluidized bed combustion ash are identified by CAS number 68131-74-8. The exact composition of the ash is dependent on the fuel source and flue additives composed of many constituents. The classification of the final substance is dependent on the presence of specific identified oxides as well as other trace elements.*

2.3 Other Hazards

Listed Carcinogens:

-Respirable Crystalline Silica

IARC: [Yes] **NTP:** [Yes] **OSHA:** [Yes] **Other:** **(ACGIH)** [Yes]

Section 3
Composition/Information on Ingredients

Substance	***CAS No.***	***Percentage (%)***	***GHS Classification***
Crystalline Silica	*14808-60-7*	*20 - 40%*	*Repeat Dose STOT, Category 1* *Carcinogen, Category 1A*
Silica, crystalline respirable (RCS)	*14808-60-7*	***See Footnote 1***	*Repeat Dose STOT, Category 1* *Carcinogen. Category 1A*
Aluminosilicates[2]	***Various, see Footnote 2***	*10 - 60%*	*Single Exposure STOT, Category 3*
Calcium oxide (CaO)	*1305-78-8*	*10 - 30%*	*Skin Irritant, Category 2* *Eye Irritant, Category 1* *Single Exposure STOT, Category 3*
Iron oxide	*1309-37-1*	*1 - 10%*	*Not Classified*
Manganese dioxide (MnO_2)	*1313-13-9*	*<2%*	*Skin Irritant, Category 2* *Eye Irritant, Category 2B*
Magnesium oxide	*1309-48-4*	*2 - 10%*	*Not Classified*
Phosphorus pentoxide (P_2O_5)	*1314-56-3*	*≤2%*	*Skin Irritant, Category 2* *Eye Irritant, Category 2B*
Sodium oxide	*1313-59-3*	*1 - 10%*	*Not Classified*
Potassium oxide (K_2O)	*12136-45-7*	*≤1%*	*Skin Irritant Category 2* *Eye Irritant Category 2B*
Titanium dioxide (TiO_2)	*13463-67-7*	*<3%*	*Not Classified*

[1] *The percentage of respirable crystalline silica has not been determined. Therefore, a GHS classification of Carcinogen 1A has been assigned.*

[2] *Aluminosilicates (CAS# 1327-36-2) may be in the form of mullite (CAS# 1302-93-8); aluminosilicate glass; pozzolans (CAS# 71243-67-9); or calcium aluminosilicates such as tricalcium aluminate (C3A), or calcium sulfoaluminate (C4A3S). The form is dependent on the source of the coal and or the process used to create the CCP. Pulverized coal combustion would be more likely to create high levels of pozzolans. Aluminosilicates may have inclusions of calcium, titanium, iron, potassium, phosphorus, magnesium and other metal oxides.*

Section 4
First Aid Measures

4.1 Description of First Aid Measures

Inhalation:	If product is inhaled and irritation of the nose or coughing occurs, remove person to fresh air. Get medical advice/attention if respiratory symptoms persist.
Skin Contact:	If skin exposure occurs, wash with soap and water.
Eye Contact:	If product gets into the eye, rinse copiously with water for several minutes. Remove contact lenses, if present and easy to do. Seek medical attention/advice if irritation occurs or persists.
Ingestion:	No specific first aid measures are required.

4.2 Most Important Health Effects, Both Acute and Delayed

Acute Effects: Direct exposure may cause respiratory irritation, eye irritation and skin irritation. The product dust can dry and irritate the skin and cause dermatitis and can irritate eyes and skin through mechanical abrasion.

Chronic Effects: Chronic exposure may cause lung damage from repeated exposure. Prolonged inhalation of respirable crystalline silica above certain concentrations may cause lung diseases, including silicosis and lung cancer.

4.3 Indication of Any Immediate Medical Attention and Special Treatment Needed

Seek first aid or call a doctor or Poison Control Center if contact with eyes occurs and irritation remains after rinsing. Get medical advice if inhalation occurs and respiratory symptoms persist.

Section 5
Firefighting Measures

5.1 Extinguishing Media

Suitable Extinguishing Media:	Product is not flammable. Use extinguishing media appropriate for surrounding fire.
Unsuitable Extinguishing Media:	Not applicable, the product is not flammable.

5.2 Special Hazards Arising from the Substance or Mixture

Hazardous Combustion Products:	None known.

5.3 Advice for Firefighters

Special Protective Equipment and Precautions for Firefighters:	As with any fire, wear self-contained breathing apparatus (NIOSH approved or equivalent) and full protective gear.

Section 6
Accidental Release Measures

6.1 Personal Precautions, Protective Equipment and Emergency Procedures

Personal precautions/Protective Equipment:	See Section 8.2.2 Individual Protective Measures. For concentrations exceeding Occupational Exposure Levels (OELs), use a self-contained breathing apparatus (SCBA).
Emergency procedures:	Use scooping, water spraying/flushing/misting or ventilated vacuum cleaning systems to clean up spills. Do not use pressurized air.

6.2 Environmental Precautions

Environmental precautions:	Prevent contamination of drains or waterways and dispose according to local and national regulations.

6.3 Methods and Material for Containment and Cleaning Up

Methods and materials for containment and cleaning up:	Do not use brooms or compressed air to clean surfaces. Use dust collection vacuum and extraction systems. Large spills of dry product should be removed by a vacuum system. Dampened material should be removed by mechanical means and recycled or disposed of according to local and national regulations.

See Sections 8 and 13 for additional information on exposure controls and disposal.

Section 7
Handling and Storage

7.1 Precautions for Safe Handling

Practice good housekeeping. Use adequate exhaust ventilation, dust collection and/or water mist to maintain airborne dust concentrations below permissible exposure limits (note: respirable crystalline silica dust may be in the air without a visible dust cloud).

Do not permit dust to collect on walls, floors, sills, ledges, machinery, or equipment. Maintain and test ventilation and dust collection equipment. In cases of insufficient ventilation, wear a NIOSH approved respirator for silica dust when handling or disposing dust from this product. Avoid contact with skin and eyes. Wash or vacuum clothing that has become dusty. Avoid eating, smoking, or drinking while handling the material.

7.2 Conditions for Safe Storage, Including any Incompatibilities

Minimize dust produced during loading and unloading.

Section 8
Exposure Controls/Personal Protection

8.1 Control Parameters

OCCUPATIONAL EXPOSURE LIMITS					
SUBSTANCE		**OSHA PEL TWA (mg/m^3)**	**NIOSH REL TWA (mg/m^3)**	**ACGIH TLV TWA (mg/m^3)**	**CA - OSHA PEL (mg/m^3)**
Calcium oxide		5	2	2	2
Particulates Not Otherwise Regulated	Total	15	15	10	10
	Respirable	5	5	3	5
Respirable Crystalline Silica	Respirable	0.05	0.05	0.025	0.05
Manganese dioxide **(as manganese compounds)**	Total	5 (Ceiling)	1 3 (STEL)	0.1	0.2
	Respirable	-	-	0.02	-

8.2 Exposure Controls

8.2.1 Engineering Controls

Provide ventilation to maintain the ambient workplace atmosphere below the occupational exposure limit(s). Use general and local exhaust ventilation and dust collection systems as necessary to minimize exposure.

8.2.2 Personal Protective Equipment (PPE)

Respiratory protection:	Wear a NIOSH approved particulate respirator if exposure to airborne particulates is unavoidable and where occupational exposure limits may be exceeded. If airborne exposures are anticipated to exceed applicable PELs or TLVs, a self-contained breathing apparatus or airline respirator is recommended.
Eye and face protection:	If eye contact is possible, wear protective glasses with side shields. Avoid contact lenses.
Hand and skin protection:	Wear gloves and protective clothing. Wash hands with soap and water after contact with material.

Section 9
Physical and Chemical Properties

9.1 Information on Basic Physical and Chemical Properties

Property: Value	Property: Value
Appearance (physical state, color, etc.): Fine tan/ gray particulate	**Upper/lower flammability or explosive limits:** Not applicable
Odor: Odorless[1]	**Vapor Pressure (Pa):** Not applicable
Odor threshold: Not applicable	**Vapor Density:** Not applicable
pH (25 °C) (in water): 8 - 11	**Specific gravity or relative density:** 2.2 – 2.9
Melting point/freezing point (°C): Not applicable	**Water Solubility:** Slight
Initial boiling point and boiling range (°C): Not applicable	**Partition coefficient: n-octane/water:** Not determined
Flash point (°C): Not determined	**Auto ignition temperature (°C):** Not applicable
Evaporation rate: Not applicable	**Decomposition temperature (°C):** Not determined
Flammability (solid, gas): Not combustible	**Viscosity:** Not applicable

[1] The use of urea or aqueous ammonia injected into the flue gas to reduce nitrogen oxides (NOx) emissions may result in the presence of ammonium sulfate or ammonium bisulfate in the ash at less than 0.1%. When ash containing these substances becomes wet under high pH (>9), free ammonia gas may be released resulting in objectionable/nuisance ammonia odor and potential exposure to ammonia gas especially in confined spaces.

Section 10
Stability and Reactivity

10.1 Reactivity:	The material is an inert, inorganic material primarily composed of elemental oxides.
10.2 Chemical stability:	The material is stable under normal use conditions.
10.3 Possibility of hazardous reactions:	The material is a relatively stable, inert material; however, when ash containing ammonia becomes wet under high pH (>9), free ammonia gas may be released resulting in an objectionable/nuisance ammonia odor and potential exposure to ammonia gas especially in confined spaces. Polymerization will not occur.
10.4 Conditions to avoid:	Product can become airborne in moderate winds. Dry material should be stored in silos. Materials stored out of doors should be covered or maintained in a damp condition.
10.5 Incompatible materials:	None known.
10. 6 Hazardous decomposition products:	None known.

Section 11
Toxicological Information

11.1 Information on Toxicological Effects

Endpoint	Data
Acute oral toxicity	LD50 > 2000 mg/kg
Acute dermal toxicity	LD50 > 2000 mg/kg
Acute inhalation toxicity	LD50 > 5.0 mg/L
Skin corrosion/irritation	Does not meet the classification criteria but may cause slight skin irritation. Product dust can dry the skin which can result in irritation.
Eye damage/irritation	Causes serious eye irritation. Positive scores for conjunctiva irritation and chemosis in 2/3 animals based on average of 24, 48 and 72-hour scores with irritation clearing within 21 days; no corneal or iritis effects observed.
Respiratory/skin sensitization	Not a respiratory or dermal sensitizer.
Germ cell mutagenicity	Not mutagenic in in-vitro and in-vivo assays with or without metabolic activation.
Carcinogenicity	Not available. Respirable crystalline silica has been identified as a carcinogen by OSHA, NTP, ACGIH and IARC.
Reproductive toxicity	No developmental toxicity was observed in available animal studies. Reproductive studies on CCPs showed either no reproductive effects, or some effects on male and female reproductive organs and parameters but without a clear dose response.
STOT-SE	CCPs when present as a nuisance dust may result in respiratory irritation.
STOT-RE	In a 180-day inhalation study with fly ash dust, no effects were observed at the highest dose tested. NOEC = 4.2 mg/m^3; it is not possible to assess the level at which toxicologically significant effects may occur. Repeated inhalation exposures to high levels of respirable crystalline silica may result in lung damage (i.e., silicosis).
Aspiration Hazard	Not applicable based product form.

Section 12
Ecological Information

12.1 Toxicity

Fly Ash (CAS# 68131-74-8)	
Toxicity to Fish	LC50 > 100 mg/L
Toxicity to Aquatic Invertebrates	Data indicates that the test substance is not toxic to *Daphnia magna* (EC50 undetermined)
Toxicity to Aquatic Algae and Plants	EC50 = 10 mg/L
Calcium oxide CAS# 1305-78-8	
Toxicity to Fish	LC50 = 50.6 mg/L The findings were closely related to the pH of the test solutions; therefore, pH is considered to be the main reason for the effects.
Toxicity to Aquatic Invertebrates	EC50 = 49.1 mg/L The findings were closely related to the pH of the test solutions; therefore, pH is considered to be the main reason for the effects.
Toxicity to Aquatic Algae and Plants	NOEC =48 mg/L @ 72 hours based on $Ca(OH)_2$ The initial pH of the test medium was not directly related to the biologically relevant effects. The formation of precipitates is likely the result of the reaction between CO_2 dissolved in the medium.

12.2 Persistence and Degradability

Not relevant for inorganic materials.

12.3 Bioaccumulative Potential

This material does not contain any compounds that would bioaccumulate up the food chain.

12.4 Mobility in Soil

No data available.

12.5 Results of PBT and vPvB Assessment

This material does not contain any compounds classified as “persistent, bioaccumulative or toxic” nor as “very persistent/very bioaccumulative”.

12.6 Other Adverse Effects

None known.

Section 13
Disposal Considerations

See Sections 7 and 8 above for safe handling and use, including appropriate industrial hygiene practices.

Dispose of all waste product and containers in accordance with federal, state and local regulations.

Section 14
Transport Information

Regulatory entity: U.S. DOT	Shipping Name:	Not Regulated
	Hazard Class:	Not Regulated
	ID Number:	Not Regulated
	Packing Group:	Not Regulated

Section 15
Regulatory Information

15.1 Safety, Health and Environmental Regulations/Legislation Specific for the Mixture

- TSCA Inventory Status

  All components are listed on the TSCA Inventory.

- California Proposition 65

  The following substances are known to the State of California to be carcinogens and/or reproductive toxicants:

  - Respirable crystalline silica
  - Titanium dioxide

- State Right-to-Know (RTK)

Component	**CAS**	**MA**[1,2]	**NJ**[3,4]	**PA**[5]	**RI**[6]
Ammonium bisulfate	7803-63-6	No	Yes	No	No
Ammonium sulfate	7783-20-2	Yes	No	Yes	No
Calcium oxide	1305-78-8	Yes	Yes	Yes	No
Iron oxide	1309-37-1	Yes	Yes	Yes	No
Magnesium oxide	1309-48-4	No	Yes	No	No
Phosphorus pentoxide (or phosphorus oxide)	1314-56-3	Yes	Yes	Yes	No
Potassium oxide	12136-45-7	No	Yes	No	No
Silica-crystalline (SiO_2), quartz	14808-60-7	Yes	Yes	Yes	No
Sodium oxide	1313-59-3	No	Yes	No	No
Titanium dioxide	13463-67-7	Yes	Yes	Yes	Yes

[1] Massachusetts Department of Public Health, no date
[2] 189th General Court of The Commonwealth of Massachusetts, no date
[3] New Jersey Department of Health and Senior Services, 2010a
[4] New Jersey Department of Health, 2010b
[5] Pennsylvania Code, 1986
[6] Rhode Island Department of Labor and Training, no date

Section 16
Other Information, Including Date of Preparation or Last Revision

16.1 Indication of Changes

Date of preparation or last revision: February 23, 2018

16.2 Abbreviations and Acronyms

- ACGIH: American Conference of Industrial Hygienists
- CA: California
- CAS: Chemical Abstract Services
- CCP: Coal Combustion Product
- CFR: Code of Federal Regulations
- EPA: Environmental Protection Agency
- GHS: Globally Harmonized System of Classification and Labelling
- IARC: International Agency for Research on Cancer
- LC50: Concentration resulting in the mortality of 50 % of an animal population
- LD50: Dose resulting in the mortality of 50 % of an animal population
- MA: Massachusetts
- NA: Not Applicable
- NJ: New Jersey
- NOEC: No observed effect concentration
- NIOSH: National Institute of Occupational Safety and Health
- NOx: Nitrogen oxides
- NTP: US National Toxicology Program
- OEL: Occupational Exposure Limit
- OSHA: Occupational Safety and Health Administration
- PA: Pennsylvania
- PBT: Persistent, Toxic and Bioaccumulative
- PEL: Permissible exposure limit
- PPE: Personal Protective Equipment
- REL: Recommended exposure limit
- RI: Rhode Island
- RCS: Respirable Crystalline Silica
- RTK: Right-to-Know
- SCBA: Self-contained breathing apparatus
- SDS: Safety Data Sheet
- STEL: Short-term exposure limit
- STOT-RE: Specific target organ toxicity-repeated exposure
- STOT-SE: Specific target organ toxicity-single exposure
- TLV: Threshold limit value
- TSCA: Toxic Substances Control Act
- TWA: Time-weighted average
- UEL: Upper explosive limit
- UVCB: Unknown or Variable Composition/Biological
- U.S.: United States
- U.S. DOT: United States of Department of Transportation

16.3 Other Hazards

Hazardous Materials Identification System (HMIS) Degree of hazard (0= low, 4 = extreme)							
Health:	2*	**Flammability:**	0	**Physical Hazards:**	0	**Personal protection:****	

** Chronic Health Effects*
****** *Appropriate personal protection is defined by the activity to be performed.*
See Section 8 for additional information.

DISCLAIMER:

This SDS has been prepared in accordance with the Hazard Communication Rule 29 CFR 1910.1200. Information herein is based on data considered to be accurate as of date prepared. No warranty or representation, express or implied, is made as to the accuracy or completeness of this data and safety information. No responsibility can be assumed for any damage or injury resulting from abnormal use, failure to adhere to recommended practices, or from any hazards inherent in the nature of the product.

ATTACHMENT D

Memorandum

BURNS McDONNELL

Date: 25 October 2021

Subject: 35 Ill. Admin. Code Part 845 - Fault Area Location Demonstration for Ash Pond at the Newton Power Plant

Illinois Power Generating Company operates the coal fired Newton Power Plant located in Jasper County, Illinois. The Newton Ash Pond is an existing surface impoundment storing coal combustion residuals (CCR). The requirements for the Newton Ash Pond are found in 35 Ill. Admin. Code (I.A.C.) 845 (Part 845).

This memorandum addresses the requirements of Section 845.320 Fault Areas, which states:

Section 845.320 Fault Areas

a) *Existing and new CCR surface impoundments, and all lateral expansions of CCR surface impoundments must not be located within 60 meters (200 feet) of the outermost damage zone of a fault that has had displacement in Holocene time unless the owner or operator demonstrates that an alternative setback distance of less than 60 meters (200 feet) will prevent damage to the structural integrity of the CCR surface impoundment.*

b) *The owner or operator of the CCR surface impoundment must obtain a certification from a qualified professional engineer stating that the demonstration meets the requirements of subsection (a).*

Pursuant to Section 845.210(d)(2), for existing CCR surface impoundments, the owner or operator of the CCR surface impoundment may use a previously completed location restriction demonstration required by Section 845.300 (Placement Above the Uppermost Aquifer), Section 845.310 (Wetlands), Section 845.320 (Fault Areas), Section 845.330 (Seismic Impact Zones), and Section 845.340 (Unstable Areas), provided that the previously completed assessments meet the applicable requirements of those Sections.

The previous fault area demonstration was certified by a qualified professional engineer stating that the demonstration meets the requirements of 40 C.F.R. § 257.62. The requirements described in 40 C.F.R. § 257.62 are nearly identical to the requirements contained in I.A.C. Section 845.320. Pursuant to Section 845.210(d)(2), a certification is not required for this demonstration. The previously completed fault area demonstration is included in Attachment D.

HALEY ALDRICH

HALEY & ALDRICH, INC.
6500 Rockside Road
Suite 200
Cleveland, OH 44131
216.739.0555

MEMORANDUM

16 October 2018
File No. 129788

SUBJECT: Location Restriction Demonstration - Fault Areas
Newton Power Station
Primary Ash Pond
Newton, Illinois

Illinois Power Generating Company operates the coal-fired Newton Power Station (Plant) located near Newton, Illinois. The Primary Ash Pond (Unit) is an existing coal combustion residuals (CCR) surface impoundment. This demonstration addresses the requirements of 40 CFR §257.62 *(Fault Areas)* of the US Environmental Protection Agency's (EPA) rule entitled *Hazardous and Solid Waste Management System; Disposal of Coal Combustion Residuals from Electric Utilities*. 80 Fed. Reg. 21,302 (Apr. 17, 2015) (promulgating 40 CFR §257.62); 83 Fed. Reg. 36,435 (July 30, 2018) (amending 40 CFR §257.62).

§257.62(a): New CCR landfills, existing and new CCR surface impoundments, and all lateral expansions of CCR units must not be located within 60 meters (200 feet) of the outermost damage zone of a fault that has had displacement in Holocene time unless the owner or operator demonstrates by the dates specified in paragraph (c) of this section that an alternative setback distance of less than 60 meters (200 feet) will prevent damage to the structural integrity of the CCR unit.

A review of available data from the U.S. Geologic Survey, the Illinois State Geological Survey, and other available information was completed for this demonstration. The nearest known mapped faults are the Albion-Ridgeway and Mt. Carmel-New Harmony faults, which are located approximately 42 miles southeast and the timeframe of the most recent activity on theses faults is not known. Based on the available published geologic data and information reviewed, there are no active faults or fault damage zones that have had displacement in Holocene time reported or indicated within 200 feet of the Unit.

<u>§257.62(b):</u> The owner or operator of the CCR unit must obtain a certification from a qualified professional engineer or approval from the Participating State Director or approval from EPA where EPA is the permitting authority stating that the demonstration meets the requirements of paragraph (a) of this section.

I, Steven F. Putrich, being a Registered Professional Engineer in good standing in the State of Illinois, do hereby certify, to the best of my knowledge, information, and belief, that the information contained in this certification has been prepared in accordance with the accepted practice of engineering. I certify, for the above-referenced CCR Unit, that the demonstration that the CCR Unit is not located within 60 meters (200 feet) of the outermost damage zone of a fault that has had a displacement in Holocene time as included in the CCR Rule Location Restrictions Evaluation memorandum dated 12 October 2018 meets the requirements of 40 CFR §257.62(a).

Signed: ____________________
Consulting Engineer

Print Name:	Steven F. Putrich
Illinois License No.:	62048779
Title:	Vice President
Company:	Haley & Aldrich, Inc.

Professional Engineer's Seal:

STEVEN F. PUTRICH
062-048-779
10/16/18

Memorandum

BURNS McDONNELL

Date: 25 October 2021

Subject: 35 Ill. Admin. Code Part 845 - Placement Above the Uppermost Aquifer Location Demonstration for Ash Pond at the Newton Power Plant

Illinois Power Generating Company operates the coal-fired Newton Power Plant located in Jasper County, Illinois. The Newton Ash Pond is an existing surface impoundment storing coal combustion residuals (CCR). The requirements for the Newton Ash Pond are found in 35 Ill. Admin. Code (I.A.C.) 845 (Part 845).

This memorandum addresses the requirements of Section 845.300 Placement Above the Uppermost Aquifer, which states:

Section 845.300 Placement Above the Uppermost Aquifer

a) *Existing and new CCR surface impoundments, and all lateral expansions of CCR surface impoundments must, be constructed with a base that is located at least 1.52 meters (five feet) above the upper limit of the uppermost aquifer, or must demonstrate that there will not be an intermittent, recurring, or sustained hydraulic connection between any portion of the base of the CCR surface impoundment and the uppermost aquifer due to normal fluctuations in groundwater elevations (including the seasonal high water table).*

b) *The owner or operator of the CCR surface impoundment must obtain a certification from a qualified professional engineer stating that the demonstration meets the requirements of subsection (a).*

Pursuant to Section 845.210(d)(2), for existing CCR surface impoundments, the owner or operator of the CCR surface impoundment may use a previously completed location restriction demonstration required by Section 845.300 (Placement Above the Uppermost Aquifer), Section 845.310 (Wetlands), Section 845.320 (Fault Areas), Section 845.330 (Seismic Impact Zones), and Section 845.340 (Unstable Areas), provided that the previously completed assessments meet the applicable requirements of those Sections.

The previous upper aquifer demonstration was certified by a qualified professional engineer stating that the demonstration meets the requirements of 40 C.F.R. § 257.60. The requirements described in 40 C.F.R. § 257.60 are nearly identical to the requirements contained in I.A.C. Section 845.300. Pursuant to Section 845.210(d)(2), a certification is not required for this demonstration. The previously completed upper aquifer demonstration is included in Attachment D.

HALEY ALDRICH

HALEY & ALDRICH, INC.
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216.739.0555

MEMORANDUM

16 October 2018
File No. 129788

SUBJECT: Location Restriction Demonstration – Placement Above Uppermost Aquifer
Newton Power Station
Primary Ash Pond
Newton, Illinois

Illinois Power Generating Company operates the coal-fired Newton Power Station (Plant) located near Newton, Illinois. The Primary Ash Pond (Unit) is an existing coal combustion residuals (CCR) surface impoundment. This demonstration addresses the requirements of 40 CFR §257.60 *(Placement above the uppermost aquifer)* of the US Environmental Protection Agency's (EPA) rule entitled *Hazardous and Solid Waste Management System; Disposal of Coal Combustion Residuals from Electric Utilities*. 80 Fed. Reg. 21,302 (Apr. 17, 2015) (promulgating 40 CFR §257.60); 83 Fed. Reg. 36,435 (July 30, 2018) (amending 40 CFR §257.60).

§257.60(a): New CCR landfills, existing and new CCR surface impoundments, and all lateral expansions of CCR units must be constructed with a base that is located no less than 1.52 meters (five feet) above the upper limit of the uppermost aquifer, or must demonstrate that there will not be an intermittent, recurring, or sustained hydraulic connection between any portion of the base of the CCR unit and the uppermost aquifer due to normal fluctuations in groundwater elevations (including the seasonal high water table). The owner or operator must demonstrate by the dates specified in paragraph (c) of this section that the CCR unit meets the minimum requirements for placement above the uppermost aquifer.

O'Brien & Gere evaluated groundwater conditions and prepared a Top of Uppermost Aquifer contour map (TOA Map) figure dated 25 January 2017 representing the upper limit of the uppermost aquifer for the Unit that included elevations ranging from approximate elevation 528+/- feet to 492+/- feet across the base of the unit. Based on historic document review, field/boring investigation and laboratory testing program at the Unit, Haley & Aldrich, Inc. determined that the lowest portion of the base of the unit is situated at or above 486.5 feet on the base of the unit.

When the critical low points at the base of unit were compared to the corresponding contours on the TOA Map, the resulting minimum separation was determined to exceed the 5.0 feet minimum separation requirement of §257.60(a).

§257.60(b): The owner or operator of the CCR unit must obtain a certification from a qualified professional engineer or approval from the Participating State Director or approval from EPA where EPA is the permitting authority stating that the demonstration meets the requirements of paragraph (a) of this section.

I, Steven F. Putrich, being a Registered Professional Engineer in good standing in the State of Illinois, do hereby certify, to the best of my knowledge, information, and belief, that the information contained in this certification has been prepared in accordance with the accepted practice of engineering. I certify, for the above-referenced CCR Unit, that the demonstration regarding the location of the base of the CCR Unit is no less than 1.52 meters above the upper limit of the uppermost aquifer as included in the CCR Rule Locations Restrictions Evaluation memorandum dated 12 October 2018 meets the requirements of 40 CFR §257.60(a).

Signed: ____________________
Consulting Engineer

Print Name:	Steven F. Putrich
Illinois License No.:	62048779
Title:	Vice President
Company:	Haley & Aldrich, Inc.

Professional Engineer's Seal:

STEVEN F. PUTRICH
062-048-779

Memorandum

BURNS McDONNELL

Date: 25 October 2021

Subject: 35 Ill. Admin. Code Part 845 – Seismic Impact Zone Location Demonstration for Ash Pond at the Newton Power Plant

Illinois Power Generating Company operates the coal-fired Newton Power Plant located in Jasper County, Illinois. The Newton Ash Pond is an existing surface impoundment storing coal combustion residuals (CCR). The requirements for the Newton Ash Pond are found in 35 Ill. Admin. Code (I.A.C.) 845.

This memorandum addresses the requirements of Section 845.330 Seismic Impact Zones, which states:

Section 845.330 Seismic Impact Zones

> a) *Existing and new CCR surface impoundments, and all lateral expansions of CCR surface impoundments must not be located in seismic impact zones unless the owner or operator demonstrates that all structural components including liners, leachate collection and removal systems, and surface water control systems, are designed to resist the maximum horizontal acceleration in lithified earth material for the site.*
>
> b) *The owner or operator of the CCR surface impoundment must obtain a certification from a qualified professional engineer stating that the demonstration meets the requirements of subsection (a).*

Pursuant to Section 845.210(d)(2), for existing CCR surface impoundments, the owner or operator of the CCR surface impoundment may use a previously completed location restriction demonstration required by Section 845.300 (Placement Above the Uppermost Aquifer), Section 845.310 (Wetlands), Section 845.320 (Fault Areas), Section 845.330 (Seismic Impact Zones), and Section 845.340 (Unstable Areas), provided that the previously completed assessments meet the applicable requirements of those Sections.

The previous seismic impact zone demonstration was certified by a qualified professional engineer stating that the demonstration meets the requirements of 40 C.F.R. § 257.63. The requirements described in 40 C.F.R. § 257.63 are nearly identical to the requirements contained in I.A.C. Section 845.330. Pursuant to Section 845.210(d)(2), a certification is not required for this demonstration. The previously completed seismic impact zone demonstration is included in Attachment D.

HALEY & ALDRICH, INC.
6500 Rockside Road
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Cleveland, OH 44131
216.739.0555

MEMORANDUM

16 October 2018
File No. 129788

SUBJECT: Location Restriction Demonstration – Seismic Impact Zone
Newton Power Station
Primary Ash Pond
Newton, Illinois

Illinois Power Generating Company operates the coal-fired Newton Power Station (Plant) located near Newton, Illinois. The Primary Ash Pond (Unit) is an existing coal combustion residuals (CCR) surface impoundment. This demonstration addresses the requirements of 40 CFR §257.63 *(Seismic Impact zones)* of the U.S. Environmental Protection Agency's (EPA) rule entitled *Hazardous and Solid Waste Management System; Disposal of Coal Combustion Residuals from Electric Utilities*. 80 Fed. Reg. 21,302 (Apr. 17, 2015) (promulgating 40 CFR §257.63); 83 Fed. Reg. 36,435 (July 30, 2018) (amending 40 CFR §257.63).

§257.63(a): New CCR landfills, existing and new CCR surface impoundments, and all lateral expansions of CCR units must not be located in seismic impact zones unless the owner or operator demonstrates by the dates specified in paragraph (c) of this section that all structural components including liners, leachate collection and removal systems, and surface water control systems, are designed to resist the maximum horizontal acceleration in lithified earth material for the site.

The results of our evaluation indicate that the Unit is in compliance with 40 CFR §257.63(a). Although the Unit is located in a seismic impact zone, it satisfies the demonstration requirements of 40 CFR §257.63(a). The AECOM report entitled "CCR Certification Report: Initial Structural Stability Assessment, Initial Safety Factor Assessment, and Initial Inflow Design Flood Control System Plan for the Primary Ash Pond at Newton Power Station" dated October 2016 (AECOM Report), includes engineering analysis, calculations, and findings that support the requirements of 40 CFR §257.63(a), and provides documentation that those requirements have been evaluated by AECOM for the subject CCR unit.

<u>§257.63(b):</u> The owner or operator of the CCR unit must obtain a certification from a qualified professional engineer or approval from the Participating State Director or approval from EPA where EPA is the permitting authority stating that the demonstration meets the requirements of paragraph (a) of this section.

I, Steven F. Putrich, being a Registered Professional Engineer in good standing in the State of Illinois, do hereby certify, to the best of my knowledge, information, and belief, that the information contained in this certification has been prepared in accordance with the accepted practice of engineering. I certify that the CCR Unit is located in a seismic impact zone as included in the CCR Rule Locations Restriction Evaluation memorandum dated 12 October 2018 and satisfies all requirements of 40 CFR §257.63(a).

By providing this certification demonstration statement, we are not stating or inferring that we have verified or certified the details, assumptions, calculations and/or site condition models developed by AECOM in the subject report; those elements of the report are considered the professional opinions and determinations of AECOM.

Signed: ____________________
Consulting Engineer

Print Name:	Steven F. Putrich
Illinois License No.:	62048779
Title:	Vice President
Company:	Haley & Aldrich, Inc.

Professional Engineer's Seal:

STEVEN F. PUTRICH
062-048-779
REGISTERED PROFESSIONAL ENGINEER
10/16/18

Memorandum

Date: 25 October 2021

Subject: 35 Ill. Admin. Code Part 845 – Unstable Areas Location Demonstration for Ash Pond at Newton Power Plant

Illinois Power Generating Company operates the coal-fired Newton Power Plant located in Jasper County, Illinois. The Newton Ash Pond is an existing surface impoundment storing coal combustion residuals (CCR). The requirements for the Newton Ash Pond are found in 35 Ill. Admin. Code (I.A.C.) Part 845 (Part 845).

This memorandum addresses the requirements of Section 845.340 Unstable Areas which states:

Section 845.340 Unstable Areas

a) *An existing or new CCR surface impoundment, or any lateral expansion of a CCR surface impoundment must not be located in an unstable area unless the owner or operator demonstrates that recognized and generally accepted engineering practices have been incorporated into the design of the CCR surface impoundment to ensure that the integrity of the structural components of the CCR surface impoundment will not be disrupted.*

b) *The owner or operator must consider all the following factors, at a minimum, when determining whether an area is unstable:*

   1) *On-site or local soil conditions, including liquefaction, that may result in significant differential settling;*

   2) *On-site or local geologic or geomorphologic features; and*

   3) *On-site or local human-made features or events (both surface and subsurface)*

d) *The owner or operator of the CCR surface impoundment must obtain a certification from a qualified professional engineer stating that the demonstration meets the requirements of subsections (a).*

Demonstration of compliance with Section 845.340(a) and (b) – Unstable Areas:

Pursuant to Section 845.210(d)(2), for existing CCR surface impoundments, the owner or operator of the CCR surface impoundment may use a previously completed location restriction demonstration required by Section 845.300 (Placement Above the Uppermost Aquifer), Section 845.310 (Wetlands), Section 845.320 (Fault Areas), Section 845.330 (Seismic Impact Zones), and Section 845.340 (Unstable Areas), provided that the previously completed assessments meet the applicable requirements of those Sections.

The previous unstable area demonstration was certified by a qualified professional engineer stating that the demonstration meets the requirements of 40 C.F.R. § 257.64. The requirements described in 40 C.F.R. § 257.64 are nearly identical to the requirements contained in I.A.C. Section 845.340. Pursuant to Section 845.210(d)(2), a certification is not required for the unstable area demonstration. The previously completed unstable area demonstration is included in Attachment D.

HALEY & ALDRICH, INC.
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216.739.0555

MEMORANDUM

16 October 2018
File No. 129788

SUBJECT: Location Restriction Demonstration – Unstable Areas
Newton Power Station
Primary Ash Pond
Newton, Illinois

Illinois Power Generating Company operates the coal-fired Newton Power Station (Plant) located near Newton, Illinois. The Primary Ash Pond (Unit) is an existing coal combustion residuals (CCR) surface impoundment at the Plant. This demonstration addresses the requirements of 40 CFR §257.64 *(Unstable Areas)* of the US Environmental Protection Agency's (EPA) rule entitled *Hazardous and Solid Waste Management System; Disposal of Coal Combustion Residuals from Electric Utilities*. 80 Fed. Reg. 21,302 (Apr. 17, 2015) (promulgating 40 CFR §257.64); 83 Fed. Reg. 36,435 (July 30, 2018) (amending 40 CFR §257.64).

§257.64(a): An existing or new CCR landfill, existing or new CCR surface impoundment, or any lateral expansion of a CCR unit must not be located in an unstable area unless the owner or operator demonstrates by the dates specified in paragraph (d) of this section that recognized and generally accepted good engineering practices have been incorporated into the design of the CCR unit to ensure that the integrity of the structural components of the CCR unit will not be disrupted.

§257.64(b): The owner or operator must consider all of the following factors, at a minimum, when determining whether an area is unstable:

(1) On-site or local soil conditions that may result in significant differential settling;
(2) On-site or local geologic or geomorphologic features; and
(3) On-site or local human-made features or events (both surface and subsurface).

Determination of compliance with §257.64(b)(1) - Conditions associated with the potential for significant differential settlement were not identified in the area where the Plant is located. A separate report completed by AECOM entitled "CCR Certification Report: Initial Structural Stability Assessment, Initial Safety Factor Assessment, and Initial Inflow Design Flood Control System Plan for the Primary Ash Pond at Newton Power Station" dated October 2016 concluded that the soils under the Unit are not susceptible to liquefaction.

Determination of compliance with §257.64(b)(2) - Based on available United States Geological Survey (USGS) and Illinois State Geological Survey (ISGS) information, karst topography or physiographic features such as sinkholes, vertical shafts, sinking streams, caves, large springs, or blind valleys do not exist at the Plant. To evaluate the susceptibility of landslides, we reviewed readily available USGS and Illinois Department of Energy and Natural Resources (IDENR) data. The USGS data indicates that the

Plant is in an area of low landslide incidence. A review of IDENR data indicated that there has not been a landslide occurrence at or near the Unit. Accordingly, it is our opinion that the Unit is not located in an area that has high susceptibility to landslides.

Determination of compliance with §257.64(b)(3) - Finally, there are no documented surface or subsurface anthropogenic activities that would be indicative of creating unstable foundation conditions. Communication with Illinois Department of Natural Resources (IDNR) indicated that there are no known mine subsidence at or near the Unit.

§257.64(c): The owner or operator of the CCR unit must obtain a certification from a qualified professional engineer or approval from the Participating State Director or approval from EPA where EPA is the permitting authority stating that the demonstration meets the requirements of paragraph (a) of this section.

I, Steven F. Putrich, being a Registered Professional Engineer in good standing in the State of Illinois, do hereby certify, to the best of my knowledge, information, and belief, that the information contained in this certification has been prepared in accordance with the accepted practice of engineering. I certify, for the above-referenced CCR Unit, that the demonstration indicating the CCR Unit is not located in an unstable area as included in the CCR Rule Location Restrictions Evaluation memorandum dated 12 October 2018 meets the requirements of 40 CFR §257.64(a).

Signed: ______________________
Consulting Engineer

Print Name:	Steven F. Putrich
Illinois License No.:	62048779
Title:	Vice President
Company:	Haley & Aldrich, Inc.

Professional Engineer's Seal:

STEVEN F. PUTRICH
062-048-779
10/16/18

Luminant

Office Memorandum

Date: October 17, 2020

To: Cynthia Vodopivec

cc:
David Mitchell
Charles Koudelka
Phil Morris

From: Vic Modeer

Subject:
Illinois Power Resources Generating, LLC
Newton Power Station
Newton Ash Pond Floodplain Certification

Illinois Power Resources Generating, LLC (IPRG) is the owner of the coal fired Newton Power Station, located in Jasper County near Newton, Illinois. The Ash Pond is an active surface impoundment storing coal combustion residuals (CCR). The requirements for the Ash Pond are found in 35 Ill. Admin. Code 845, Standards for the Disposal of Coal Combustion Residuals in Surface Impoundments (Part 845).

Section 845.340 (c): An existing or new CCR surface impoundment, or any lateral expansion of a CCR surface impoundment, must not be located in a floodplain unless the owner or operator demonstrates that recognized and generally accepted engineering practices have been incorporated into the design of the CCR surface impoundment to ensure that the CCR surface impoundment will not restrict the flow of the base flood , reduce the temporary water storage capacity of a floodplain , or result in washout of CCR , so as to pose a hazard to human life, wildlife, or land or water resources.

Engineering Evaluation. The boundaries of the impoundment were determined by a survey conducted by a professional surveyor licensed in the State of Illinois. The boundaries of the Ash Pond were compared to the existing FEMA floodplain map, and it was determined that Bottom Ash Pond is located within Zone A of the floodplain according to the 1985 FEMA Floodplain mapping. In order to determine that: "generally accepted engineering practices have been incorporated into the design of the CCR surface impoundment to ensure that the CCR surface impoundment will not restrict the flow of the base flood, reduce the temporary water storage capacity of a floodplain, or result in washout of CCR," the following engineering was involved:

1. Determine the base flood elevation (BFE) and compare to the ash pond embankment elevations,
2. Determine the surface impoundment will not restrict the temporary water storage capacity of the floodplain. and
3. Result in a washout of CCR.

Elevations. The ash pond embankments were surveyed in 2020. The top of the ash pond embankment is at EL. 550-feet and the toe of the embankment at the lake normal pool level is at EL.504.0-feet. The BFE was determined by the publication "FEMA 256 - Managing Floodplain Development in Zone A Areas, National Flood Insurance Program, FEMA, 1995." The method shown in section V. Developing Base (100-Year) Flood Elevations, Simplified Methods, V-1 was used to conservatively estimate the BFE. The evaluation is attached as Figures 1 and 2. The result shows the BFE at EL. 525-feet. The ash pond is not subject to overtopping by the BFE.

Floodplain Restriction by the Ash Pond. The ash pond is shown to be within Zone A of the 1985 FEMA mapping. The original ground survey of the ash pond was evaluated for determining the volume of the floodplain that the ash pond has removed from Zone A of Newton Lake. The volume calculated from the survey was 1,129,000-cubic feet. The total volume of the lake, less the ash pond, precluded volume, but including the Zone A flood volume is 1,296,720,000-cubic feet. The construction of the ash pond resulted in a ”no-rise’ condition as the area removed from the BFE is 0.087% of the lake volume or less than 0.1-foot.

Washout of CCR. The ash pond embankment does not overtop. The embankment is constructed with erosion resistant soils (clays) and planted grasses. By design and definition, lake flooding will not cause erosive flow velocities. However, the areas where wave erosion has occurred are covered with riprap further protecting the embankment from releasing CCR.

Based on the above engineering evaluation, the Newton Ash Pond meets the requirements of Section 845.340 (c).

> *<u>Section 845.330 (d):</u> The owner or operator of the CCR surface impoundment must obtain a certification from a qualified professional engineer stating that the demonstration meets the requirements of subsections (a) and (c).*

I, Victor Modeer, being a Professional Engineer in good standing in the State of Illinois, do hereby certify, to the best of my knowledge, information, and belief that this floodplain demonstration meets the requirements of 35 Ill. Adm. Code 845.340(c).

Sincerely,

Vic Modeer, PE, D.GE
(IL, MO, IN, KY, OH, LA)
Engineering Manager

VICTOR ALBERT MODEER JR.
062-043112

Memorandum

BURNS McDONNELL

Date: 25 October 2021

Subject: 35 I.A.C. Admin. Code Part 845 - Wetland Location Demonstration for Ash Pond at Newton Power Plant

Illinois Power Generating Company operates the coal-fired Newton Power Plant located in Jasper County, Illinois. The Newton Ash Pond is an existing surface impoundment storing coal combustion residuals (CCR). The requirements for the Newton Ash Pond are found in 35 Ill. Admin. Code (I.A.C.) 845 (Part 845).

This memorandum addresses the requirements of Section 845.310 Wetlands, which states:

Section 845.310 Wetlands

a) *Existing and new CCR surface impoundments, and all lateral expansions of CCR surface impoundments must not be located in wetlands unless the owner or operator demonstrates* [that the requirements listed in 845.310(a)(1) through (5) are met.]

b) *The owner or operator of the CCR surface impoundment must obtain a certification from a qualified professional engineer stating that the demonstration meets the requirements of subsection (a).*

Pursuant to Section 845.210(d)(2), for existing CCR surface impoundments, the owner or operator of the CCR surface impoundment may use a previously completed location restriction demonstration required by Section 845.300 (Placement Above the Uppermost Aquifer), Section 845.310 (Wetlands), Section 845.320 (Fault Areas), Section 845.330 (Seismic Impact Zones), and Section 845.340 (Unstable Areas), provided that the previously completed assessments meet the applicable requirements of those Sections.

The previous wetlands demonstration was certified by a qualified professional engineer stating that the demonstration meets the requirements of 40 C.F.R. § 257.61. The requirements described in 40 C.F.R. § 257.61 are nearly identical to the requirements contained in I.A.C. Section 845.310. Pursuant to Section 845.210(d)(2), a certification is not required for this demonstration. The previously completed wetlands demonstration is included in Attachment D.

HALEY ALDRICH

HALEY & ALDRICH, INC.
6500 Rockside Road
Suite 200
Cleveland, OH 44131
216.739.0555

MEMORANDUM

16 October 2018
File No. 129788

SUBJECT: Location Restriction Demonstration - Wetland Areas
Newton Power Station
Newton Ash Pond
Newton Illinois

Illinois Power Generating Company operates the coal-fired Newton Power Station (Plant) located near Newton, Illinois. The Newton Ash Pond (Unit) is an existing coal combustion residuals (CCR) surface impoundment. This demonstration addresses the requirements of 40 CFR §257.61 *(Wetlands)* of the US Environmental Protection Agency's (EPA) rule entitled *Hazardous and Solid Waste Management System; Disposal of Coal Combustion Residuals from Electric Utilities*. 80 Fed. Reg. 21,302 (Apr. 17, 2015) (promulgating 40 CFR §257.61); 83 Fed. Reg. 36,435 (July 30, 2018) (amending 40 CFR §257.61).

§257.61(a): New CCR landfills, existing and new CCR surface impoundments, and all lateral expansions of CCR units must not be located in wetlands, as defined in §232.2 of this chapter, unless the owner or operator demonstrates by the dates specified in paragraph (c) of this section that the CCR unit meets the requirements of paragraphs (a)(1) through (5) of this section.

Based on a review of the U.S. Fish and Wildlife Service's National Wetland Inventory mapping, 0.5-meter resolution aerial imagery (2016) and the results of on-site field assessments, the Unit is not located in wetlands as defined by §232.2.

<u>§257.61(b):</u> The owner or operator of the CCR unit must obtain a certification from a qualified professional engineer or approval from the Participating State Director or approval from EPA where EPA is the permitting authority stating that the demonstration meets the requirements of paragraph (a) of this section.

I, Steven F. Putrich, being a Registered Professional Engineer in good standing in the State of Illinois, do hereby certify, to the best of my knowledge, information, and belief, that the information contained in this certification has been prepared in accordance with the accepted practice of engineering. I certify, for the above-referenced CCR Unit, that the CCR Unit is not located in wetlands as included in the CCR Rule Location Restrictions Evaluation memorandum dated 12 October 2018 and, therefore, meets the requirements of 40 CFR §257.61(a).

Signed: ______________________
Consulting Engineer

Print Name:	Steven F. Putrich
Illinois License No.:	62048779
Title:	Vice President
Company:	Haley & Aldrich, Inc.

Professional Engineer's Seal:

STEVEN F. PUTRICH
062-048-779
10/16/18

ATTACHMENT E


NEWTON PRIMARY
ASH POND
STATE ID #: N/A
ID #: W0798070001-01
ILLINOIS POWER
GENERATING COMPANY

ATTACHMENT F

ILLINOIS POWER GENERATING COMPANY

NEWTON POWER PLANT

CITY OF NEWTON, JASPER COUNTY, ILLINOIS

Emergency Action Plan (EAP)

40 C.F.R. § 257.73(a)(3), Ill. Adm. Code 845.520
Coal Combustion Residual (CCR) Impoundment
& Related Facilities

- Primary Ash Pond (NID # IL50719) (IEPA W0798070001-01)

Revision Date: September 16, 2021

Qualified Professional Engineer Certification; Emergency Action Plan for the Newton Power Plant Primary Ash Pond

In accordance with 40 C.F.R. § 257.73(a)(3)(iv) and 35 Ill. Adm. Code 845.520(e), the owner or operator of a CCR unit that is required to prepare a written Emergency Action Plan under 40 C.F.R. § 257.73(a)(3) and 35 Ill. Adm. Code 845.520(a) must obtain a certification from a qualified professional engineer stating that the written Emergency Action Plan meets the requirements of 40 C.F.R. § 257.73(a)(3) and 35 Ill. Adm. Code 845.520.

I, Phil Morris, being a Professional Engineer in good standing in the State of Illinois, do hereby certify, to the best of my knowledge, information, and belief that:

1. the information contained in this Emergency Action Plan was prepared in accordance with the accepted practice of engineering; and
2. this Emergency Action Plan meets the requirements of 40 C.F.R. § 257.73(a)(3) and 35 Ill. Adm. Code 845.520.

Phil Morris
Senior Director, Corporate Environmental

9/27/21

Date

PHIL L. MORRIS
062-058763
9/27/21

NEWTON POWER PLANT
EMERGENCY ACTION PLAN
CCR IMPOUNDMENT & RELATED FACILITIES

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EMERGENCY ACTION PLAN
CCR IMPOUNDMENT & RELATED FACILITIES

PART I – EAP NARRATIVE AND EXHIBITS

1 STATEMENT OF PURPOSE

The Newton Power Plant (Power Plant) is located near the City of Newton in Jasper County, Illinois. The location is shown in Figure 1-1. The Power Plant is a coal-fired electricity producing power plant owned and operated by the Illinois Power Generating Company, a subsidiary of Dynegy. This Emergency Action Plan (EAP) was prepared in accordance with 40 CFR § 257.73(a)(3) and covers the following Coal Combustion Residual (CCR) surface impoundment located at the site:

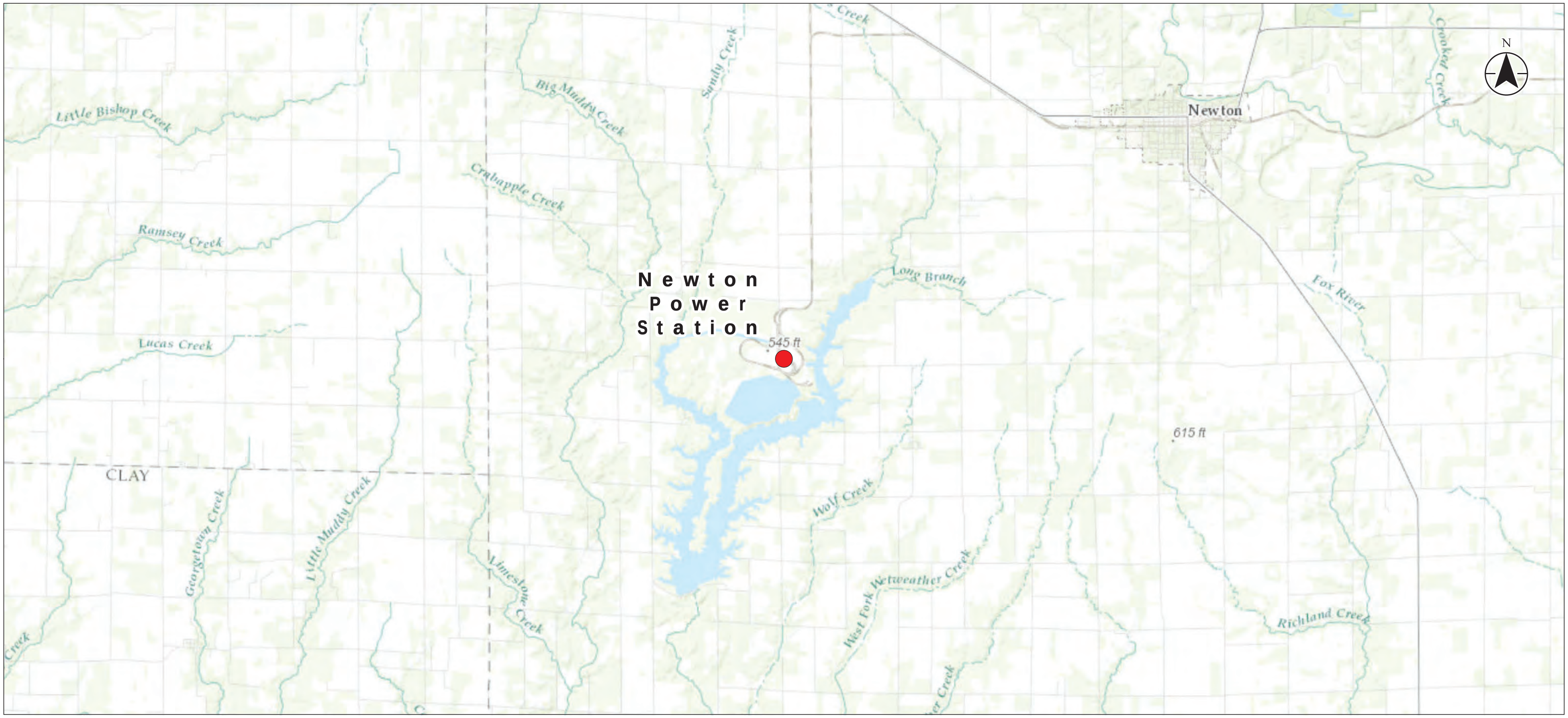
- Primary Ash Pond (NID # IL50719) (IEPA # W0798070001-01)

The location of this impoundment is shown in Figure 1-2. Section 6 of this EAP includes a description of the impoundment.

The purpose of this Emergency Action Plan (EAP) is to:

1. Safeguard the lives, as well as to reduce property damage, of citizens living within potential downstream flood inundation areas of the CCR impoundment and related facilities at the Newton Power Plant.
2. Define the events or circumstances involving the CCR impoundment and related facilities at the Newton Power Plant that represent atypical operating conditions that pose a safety hazard or emergency and how to identify those conditions.
3. Define responsible persons, their responsibilities, and notification procedures in the event of a safety emergency.
4. Provide contact information of emergency responders.
5. Identify emergency actions in the event of a potential or imminent failure of the impoundment.
6. Identify the downstream area that would be affected by failure of the impoundment.
7. Provide for effective facility surveillance, prompt notification to local Emergency Management Agencies, citizen warning and notification responses, and preparation should an emergency occur.

Information provided by Illinois Power Generating Company was utilized and relied upon in preparation of this report.



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1:126,720 (1" = 2 miles at original document size of 11x17)

Stantec DYNEGY

Project Location
Latitude: 38.936621
Longitude: -88.277038
Jasper County, Illinois

175605019
Prepared by EC on 2017-03-08
Technical Review by TS on 2017-03-27
Independent Review by MM on 2017-03-20

Client/Project
Newton Power Station
Emergency Action Plan

Figure No.
1-1

Title
Location Map

Notes
1. Coordinate System: WGS 1984 Web Mercator Auxiliary Sphere
2. Basemap Source: Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

U:\175605019\gis\mxd\EAP Figures\Figure 1-1 Newton Location Map.mxd Revised: 2017-04-12 By: ecaudill

Legend

🟥 CCR Surface Impoundment Boundary

0 0.5 1 Miles

1:31,680 (1" = 0.5 miles at original document size of 11x17)

Stantec DYNEGY

Project Location
Latitude: 38.936621
Longitude: -88.277038
Jasper County, Illinois

175666013
Prepared by EC on 2017-03-08
Technical Review by TS on 2017-03-27
Independent Review by MM on 2017-03-20

Client/Project
Newton Power Station
Emergency Action Plan

Figure No.
1-2

Title
CCR Impoundment

Notes
1. Coordinate System: WGS 1984 Web Mercator Auxiliary Sphere
2. Basemap Source: USDA-FSA-APFO Aerial Photography Field Office, Illinois State Geological Survey
3. Impoundment Boundaries Provided by Client (Dated 9/9/2015)

St. Louis 175666013\...Appendix_8.mxd

2 COMMUNICATION

To facilitate understanding among everyone involved in implementing this EAP, four response levels are used to identify the condition of an impoundment. These are:

Response Levels:

- **Level 0:** Normal conditions and routine operations, including surveillance and initial investigation of unusual conditions and effects of storm events.
- **Level 1:** Potentially hazardous condition exists, requiring investigation and possible corrective action.
- **Level 2:** Potential failure situation is developing; possible mode of failure is being assessed; corrective measures are underway.
- **Level 3:** Failure is occurring or is imminent, public protective actions are required.

The 4-Step Incident Response Process is outlined in Figure 2-1. This should be used in conjunction with the Notification Flowchart (Figure 2-2) and EAP Decision Tree (Figure 2-3). Section 4 provides guidance tables for determining Response Levels and a table providing emergency actions to be taken given various situations. Table 2-1 lists contact information for the emergency responders.

Figure 2-1. Summary/Sequence of Tasks 4-Step Incident Response Process

Step 1: Detection, Evaluation, and Response Level Determination

Sequence of Tasks:

- Notify EAP Coordinator, Plant Manager, and Dam Safety Manager of unusual condition detected and confer on next steps needed.
- Conduct technical evaluation of conditions as needed.
- Determine Response Level based on evaluation. **(Table 4-1)**
- Reset Response Level as revised evaluations warrant.

Step 2: Notification

Sequence of Tasks:

- Notify authorities, designated personnel, and external response partners of change in Response Level, using the Notification Flowchart. **(Figure 2-2)**
- *Re-notify authorities, designated personnel, and external response partners as Response Level is changed.*

Step 3: Emergency Actions

Sequence of Tasks:

- Perform emergency actions with goal of saving the impoundment and minimizing impacts to life, property, and environment. **(Table 4-3)**
- Take continuous actions to include situation assessment, information sharing, remediation, and public safety advisories or warnings, as warranted.
- *Revise action plan as changes in conditions warrant.*

Step 4: Follow-up

Sequence of Tasks:

- Document conditions and decisions in the Emergency Incident Log.
- Notify authorities, designated personnel, and external response partners that condition is stabilized; limit incident termination declarations to conditions at the site.
- Conduct and document after-action review of incident and response.

Figure 2-2. Notification Flowchart

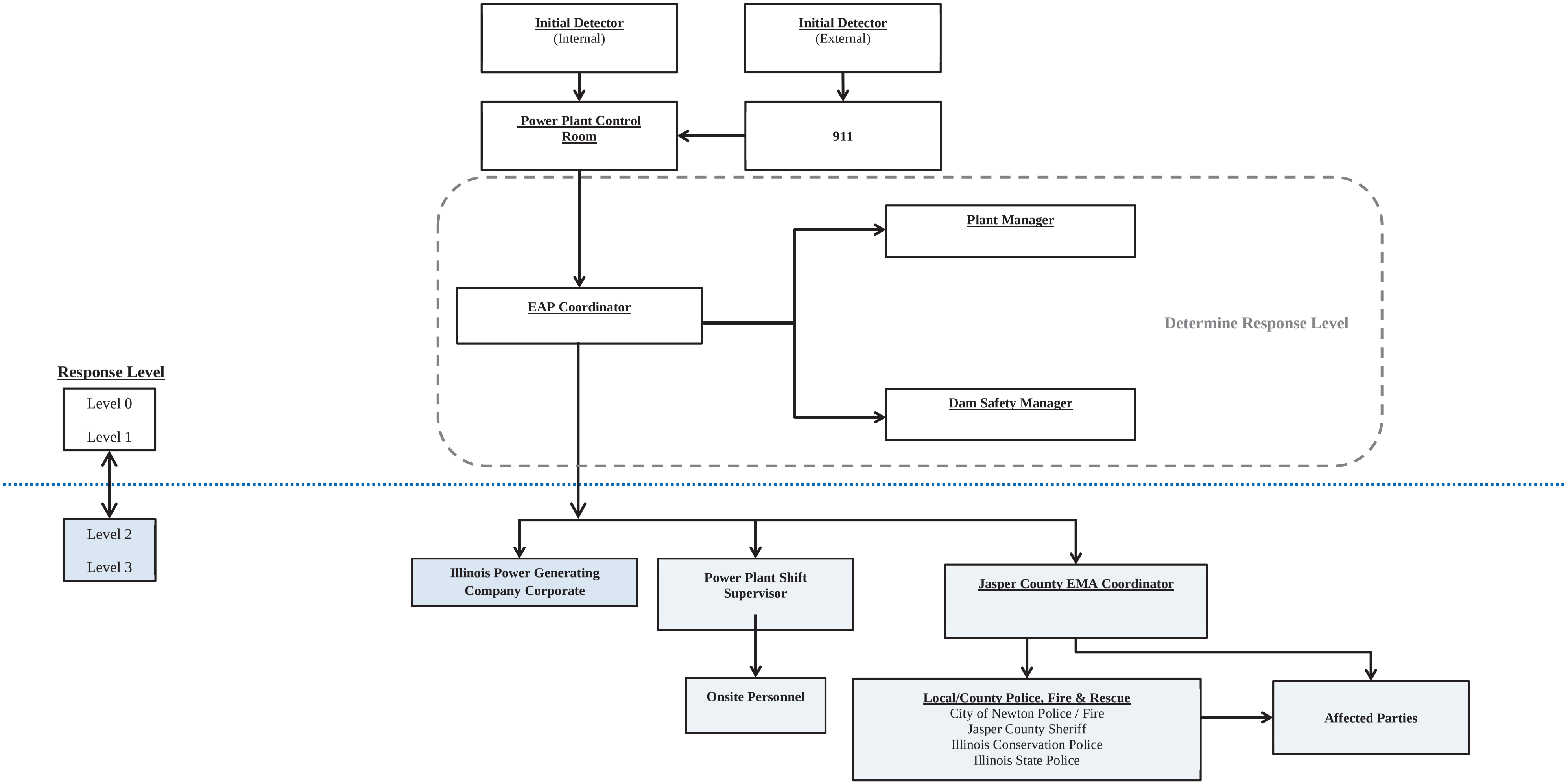

Figure 2-3. EAP Response Process Decision Tree

Note: At any given below, if failure is imminent or actively occurring **CALL 911 IMMEDIATELY** to notify emergency responders and then continue with process afterwards.

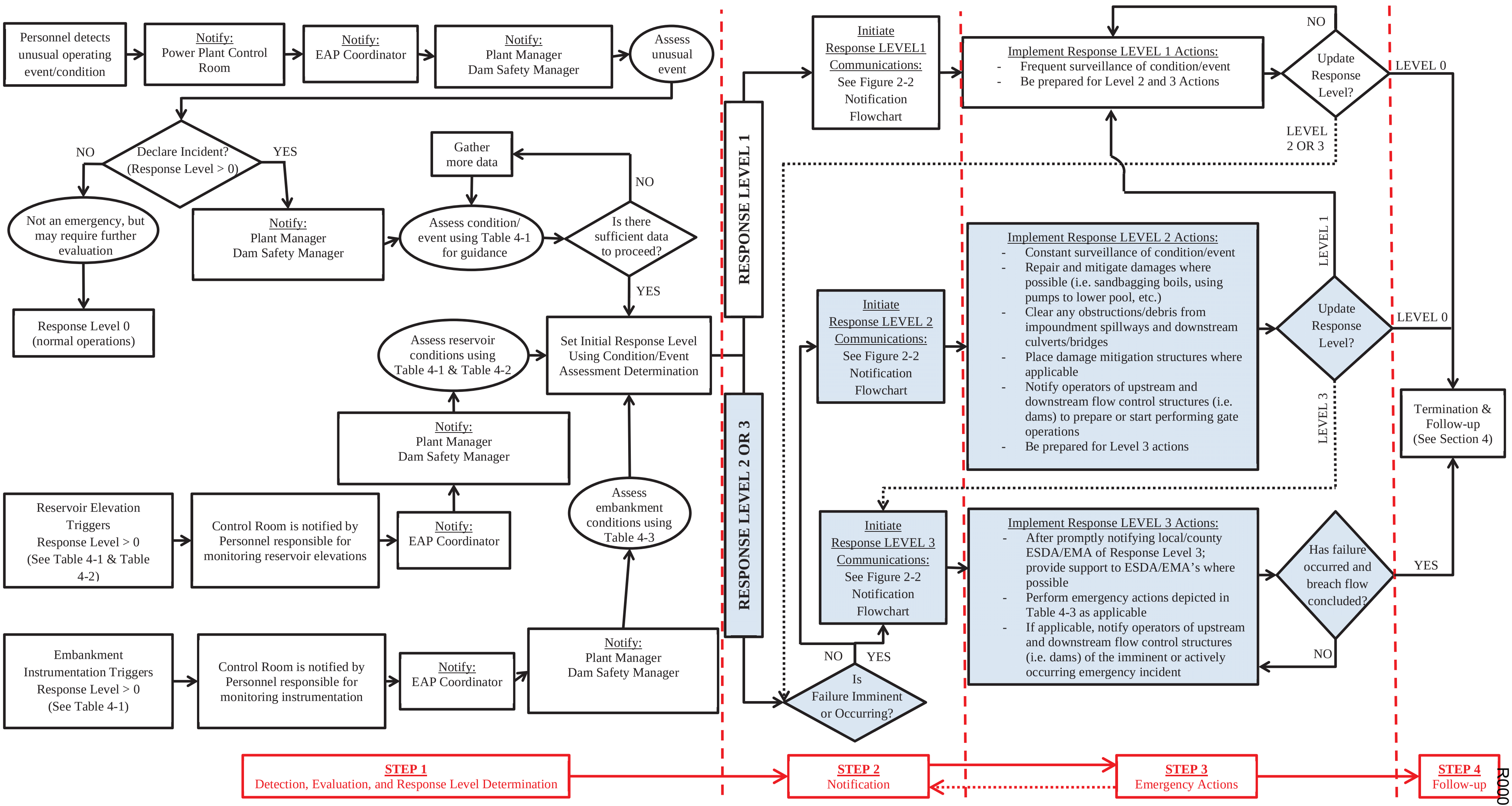

Table 2-1. EAP Emergency Responders

Position	Phone #
Internal Contacts	
Newton Power Plant	
Plant Manager	
EAP Coordinator	(618) 553-4444
Control Room	(618) 783-0501
Corporate Operations	
Dam Safety Manager	(618) 792-8488
External Contacts	
Local / County ESDA/EMA, Police, & Fire	
Jasper County ESDA/EMA	(618) 783-8123, (618) 554-2285
City of Newton Police Dept.	911, (618) 783-4500
City of Newton Fire Dept.	911, (618) 783-3887
Jasper County Sheriff Dept.	911, (618) 783-3057
State Emergency Management Agencies & Organizations	
IDNR-OWR Dam Safety Section Manager	(217) 782-4427
Newton Lake State Fish and Wildlife Area	(618) 783-3478
Illinois Conservation Police	(877) 236-7529
Illinois State Police	911, (618) 542-2171

3 EAP ROLES AND RESPONSIBILITIES

Table 3-1 provides a summary of the EAP roles during an emergency event.

Table 3-1. Summary of EAP Roles

Entity	Role Description
Emergency Response Team (ERT)	**ERT:** personnel responsible for EAP implementation, distribution, updates/maintenance, and training activities. The *ERT* is comprised of the following roles. 1. **Corporate:** corporate entity, committee, team, or position with relevant responsibility for a given generating power plant. 2. **Plant Manager:** Personnel responsible for day-to-day operation and management of the Power Plant. 3. **Dam Safety Manager:** Personnel that is most knowledgeable about the design and technical operation of facilities at a given power plant. 4. **EAP Coordinator:** Personnel responsible for implementing the EAP and associated activities. **Emergency Event – EAP Responsibilities** 1. Respond to emergencies at the Power Plant. 2. Verify and assess emergency conditions. 3. Notify and coordinate as appropriate with participating emergency services disaster agencies or emergency management agencies (ESDA/EMA's), emergency responders, regulatory agencies, and all other entities involved or affected by this EAP. 4. Take corrective action at the Power Plant. 5. Declare termination of emergencies at the Power Plant.
Jasper County ESDA/EMA	1. Receive Response Level reports from *Illinois Power Generating Company Corporate* through *EAP Coordinator*. 2. Coordinate emergency response activities with local authorities: police, fire, and rescue, etc. 3. Coordinate notification of public as necessary through established channels, which may include door-to-door contact. 4. Coordinate notification activities to affected parties within inundation areas. 5. Evaluate risk to areas beyond the inundation areas, communicate needs to the *Illinois Power Generating Company Corporate* and/or *EAP Coordinator*, and coordinate aid as appropriate. 6. Responsible for declaring termination of an emergency condition off-site upon receiving notification of an emergency status termination from the *Illinois Power Generating Company Corporate*. 7. If necessary, coordinate with *State ESDA/EMA*.
City of Newton Police, Fire, and Rescue	1. Receive alert status reports from the *ERT* or the *Jasper County ESDA/EMA*. 2. If necessary, notify affected parties and public within inundation areas (see Section 7). 3. Render assistance to Jasper County ESDA/EMA, as necessary. 4. Render assistance to *Illinois Power Generating Company Corporate and Power Plant Management*, as necessary.
Jasper County Police, Fire and Rescue, and Emergency Services	1. Receive alert status reports from the *ERT* or the *Jasper County ESDA/EMA*. 2. If necessary, notify affected parties within the inundation area. 3. Provide mutual aid to other affected areas, if requested and able.

4 EAP RESPONSE

The 4-Step Incident Response Process is shown in Figure 2-1. The Decision Tree shown in Figure 2-3 provides a flowchart for the various elements of the response process. Upon reaching Step 4 of the response process (termination and follow-up), the EAP Coordinator is responsible for notifying the ESDA/EMA's that the condition of the dam/impoundment has been stabilized. The purpose of this section is to provide specific information that can be used during a response. This information is provided in the following tables:

- Table 4-1 provides guidance for determining the response level.
- Table 4-2 provides impoundment pool level trigger elevations.
- Table 4-3 lists emergency actions to be taken depending on the situation.

Table 4-1. Guidance for Determining the Response Level

Event	Situation	Response Level
Spillway flow (See Table 4-2 for relevant elevations)	Primary spillway flow is not causing active erosion and impoundment water surface elevation is below auxiliary spillway crest elevation (if equipped).	Level 0
	Impoundment water surface elevation is at or above auxiliary spillway crest elevation (if equipped). No active erosion caused by spillway flow.	Level 1
	Spillway flow actively causing minor erosion that is not threatening the control section or dam/impoundment stability.	Level 2
	Spillway flow that could result in flooding of people downstream if the reservoir level continues to rise.	Level 2
	Abnormal operation of the spillway system due to blockage or damage that could lead to flooding.	Level 2
	Spillway flow actively eroding the soil around the spillway that is threatening the control section (e.g., undermining) or dam/impoundment stability.	Level 3
	Spillway flow that is flooding people downstream.	Level 3
Embankment overtopping (See Table 4-2 for relevant elevations)	Impoundment water surface elevation at or below typical normal pool fluctuation elevation.	Level 0
	Impoundment water surface elevation above typical normal pool fluctuation elevation.	Level 1
	Impoundment water surface elevation above high normal pool fluctuation elevation.	Level 2
	Impoundment water surface elevation at or above embankment crest elevation.	Level 3
Seepage	New seepage areas in or near the dam/impoundment with clear flow.	Level 1
	New seepage areas with cloudy discharge or increasing flow rate.	Level 2
	Heavy seepage with active erosion, muddy flow, and/or sand boils.	Level 3
Sinkholes	Observation of new sinkhole in impoundment area or on embankment.	Level 2
	Rapidly enlarging sinkhole and/or whirlpool in the impoundment.	Level 3

Table 4-1. Guidance for Determining the Response Level

Event	Situation	Response Level
Embankment cracking	New cracks in the embankment greater than ¼ inch wide without seepage.	Level 1
	Any crack in the embankment with seepage.	Level 2
	Enlarging cracks with muddy seepage.	Level 3
Embankment movement	Visual signs of movement/slippage of the embankment slope.	Level 1
	Detectable active movement/slippage of the embankment slope or other related effects (tension cracking, bulges/heaves, etc.) that could threaten the integrity of the embankment.	Level 2
	Sudden or rapidly proceeding slides of the embankment slopes.	Level 3
Embankment Monitoring Equipment (piezometers, inclinometers, surface displacement mounts, etc.)	Instrumentation readings beyond historic normal.	Level 1
	Instrumentation readings indicate the embankment is susceptible to failure.	Level 2
	Instrumentation readings indicate embankment is at threshold of failure or is currently failing.	Level 3
Earthquake or another event	Measurable earthquake felt or reported on or within 100 miles of the impoundment.	Level 1
	Earthquake or other event resulting in visible damage to the impoundment or appurtenances.	Level 2
	Earthquake or other event resulting in uncontrolled release of water or materials from the impoundment.	Level 3
Security threat	Verified bomb threat or other physical threat that, if carried out, could result in damage to the impoundment.	Level 2
	Detonated bomb or other physical damage that has resulted in damage to the impoundment or appurtenances.	Level 3
Sabotage/ vandalism	Damage to impoundment or appurtenance with no impact to the functioning of the impoundment.	Level 1
	Modification to the impoundment or appurtenances that could adversely impact the functioning of the impoundment. This would include unauthorized operation of spillway facilities.	Level 2
	Damage to impoundment or appurtenances that has resulted in seepage flow.	Level 2
	Damage to impoundment or appurtenances that has resulted in uncontrolled water release.	Level 3

Table 4-2. Impoundment Trigger Elevations

Impoundment	Embankment Crest Elevation	Auxiliary Spillway Crest Elevation	Normal Pool Fluctuation	
			Typical	High
Primary Ash Pond	554.0 feet	Not Applicable	534.0 ft.	537.0 ft.

Table 4-3. Step 3: Emergency Actions

Condition	Description of Condition	Action to be Taken
High Water Level/ Large Spillway Release	See Table 4-1 and Table 4-2 for elevations and triggering water levels associated with the impoundment and spillways covered by this EAP.	1. Assess cause of increased reservoir stage, especially during fair weather conditions. 2. Determine Response Level. 3. Make proper notifications as outlined in the Figure 2-2 Notification Flowchart. 4. Perform additional tasks as determined through consultation with the ERT. 5. Make notifications if condition worsens such that downstream flooding is imminent. **Response Level 0**: require enhanced surveillance 3 times per day **Response Level 1**: contact internal chain of command and external response partners as necessary; inspect impoundment minimum 1 time per hour **Response Level 2**: contact internal chain of command; notify ESDA/EMA's and notify external response partners. ESDA/EMA's notify affected parties. **Response Level 3**: contact internal chain of command; notify ESDA/EMA's and notify external response partners. ESDA/EMA's notify affected parties of emergency incident.
Seepage	Localized new seepage or boil(s) observed along downstream face / toe of earthen embankment with muddy discharge and increasing but controllable discharge of water.	1. Measure and record feature dimensions, approximate flow rate, and relative location to existing surface features. Take photos. Document location on a site plan and in inspection notes. 2. Determine Response Level. 3. Make proper notifications as outlined in the Figure 2-2 Notification Flowchart. 4. ERT (with Dam Safety Manager as lead) to determine mitigation actions. The following actions may apply: a) Place a ring of sandbags with a weir at the top towards the natural drainage path to monitor flow rate. If boil becomes too large to sandbag, place a blanket filter over the area using non-woven filter fabric and pea gravel. Attempt to contain flow in such a manner (without performing any excavations) that flow rates can be measured. Stockpile gravel and sand fill for later use, if necessary. b) Inspect the embankment and collect piezometer, water level and seepage flow data daily unless otherwise instructed by the Dam Safety Manager. Record any changes of conditions. Carefully observe embankment for signs of depressions, seepage, sinkholes, cracking or movement. c) Maintain continuous monitoring of feature. Record measured flow rate and any changes of condition, including presence or absence of muddy discharge.

Table 4-3. Step 3: Emergency Actions

Condition	Description of Condition	Action to be Taken
		5. Make notifications as outlined in the lower portion of the Notification Flowchart (Figure 2-2) if condition worsens such that failure is imminent.
Sabotage and Miscellaneous Other Issues	Criminal action with significant damage to embankment or structures where significant repairs are required and the integrity of the facility is compromised—condition appears stable with time.	1. Contact law enforcement authorities and restrict all access (except emergency responders) to impoundment. Restrict traffic on embankment crest to essential emergency operations only. 2. Determine Response Level. 3. Make internal notifications as outlined in the upper portion of the Notification Flowchart (Figure 2-2). 4. In conjunction with the Dam Safety Manager, assess extent of damage and visually inspect entire embankment and ancillary structures for additional less obvious damage. Based on inspection results, confirm if extent of damage to various components of the impoundment warrants a revised Response Level and additional notifications. 5. Perform additional tasks as directed by the ERT. 6. Make notifications if conditions worsen.
Embankment Deformation	**Cracks:** New longitudinal (along the embankment) or transverse (across the embankment) cracks more than 6 inches deep or more than 3 inches wide or increasing with time. New concave cracks on or near the embankment crest associated with slope movement.	1. Measure and record feature dimensions, approximate flow rate, and relative location to existing surface features. Take photos. Document location on a site plan and in inspection notes. 2. Restrict traffic on embankment crest to essential emergency operations only. 3. Determine Response Level. 4. Make notifications as outlined in the Figure 2-2 Notification Flowchart. 5. ERT (with Dam Safety Manager as lead) to determine mitigation actions. The following actions may apply: a) Place buttress fill against base of slope immediately below surface feature. Stockpile additional fill. b) Place sandbags as necessary around crack area to divert any storm water runoff from flowing into crack(s). 6. As directed by the Dam Safety Manager, additional inspection and monitoring of the dam may be required. Items may include inspect the dam on a schedule determined by the Dam Safety Manager; collect piezometer and water level data; and record any changes of condition. Carefully observe dam for signs of depressions, seepage, sinkholes, cracking or movement. 7. Make notifications as outlined in the Figure 2-2 Notification Flowchart if conditions worsen such that failure is imminent.
Embankment Deformation (cont.)	**Slides / Erosion:** Deep slide / erosion (greater than 2 feet deep) on the embankment that may also extend beyond the embankment toe but does not encroach onto the embankment crest and appears stable with time.	1. Measure and record feature dimensions, approximate flow rate, and relative location to existing surface features. Take photos. Document location on a site plan and in inspection report. 2. Restrict traffic on embankment crest to essential emergency operations only. 3. Determine the Response Level. 4. Make notifications as outlined in the Figure 2-2 Notification Flowchart. 5. ERT (with Dam Safety Manager as lead) to determine mitigation actions. Additional actions may include the following items. a) Place sandbags as necessary around slide area to divert any storm water runoff from flowing into slide(s). b) Increase inspections of the dam; collect piezometer and water level data; and record any changes of condition. During inspections, carefully observe dam for signs of depressions, seepage, sinkholes, cracking or movement.

Table 4-3. Step 3: Emergency Actions

Condition	Description of Condition	Action to be Taken
		6. Make notifications as outlined in the Figure 2-2 Notification Flowchart if conditions worsen such that failure is imminent.
	Sinkholes: Small depression observed on the embankment or within 50 feet of the embankment toe that is less than 5 feet deep and 30 feet wide or which is increasing with time.	1. Slowly open drain gates to lower pool elevation. 2. Measure and record feature dimensions, approximate flow rate, and relative location to existing surface features. Take photos. Document location on a site plan and in inspection notes. 3. Restrict traffic on embankment crest to essential emergency operations only. 4. Determine Response Level. 5. Make notifications as outlined in the Figure 2-2 Notification Flowchart. 6. ERT (with Dam Safety Manager as lead) to determine mitigation actions. Additional actions may include the following items: a) Backfill the depression with relatively clean earth fill (free of organic materials) generally even with surrounding grade and slightly mounded (6 to 12 inches higher) in the center to shed storm water away from the depression. Stockpile additional fill. b) Increase inspections of the dam; collect piezometer and water level data daily unless otherwise instructed by Dam Safety Manager; and record any changes of condition. Carefully observe dam for signs of depressions, seepage, sinkholes, cracking or movement. 7. Make notifications as outlined in the Figure 2-2 Notification Flowchart if conditions worsen such that failure is imminent.
Gate Malfunction or Failure	Sluice gate damaged structurally (sabotage, debris, etc.) with uncontrolled release of water at a constant volume. Condition appears stable.	1. Close any other gates, if open. 2. Determine Response Level. 3. Make notifications as outlined in the Figure 2-2 Notification Flowchart. 4. Obtain instructions from the Dam Safety Manager to determine if there are other methods to stop or slow down the flow of water. 5. If conditions worsen such that failure is imminent, make notifications as outlined in the lower portion of the Figure 2-2 Notification Flowchart.

5 PREPAREDNESS

The intent of this section is to provide information that will be utilized during a response. Established emergency supplies and locations, suppliers, and equipment are provided in Table 5-1. Suppliers contact information is listed in Table 5-2.

A coordination meeting shall be conducted annually between representatives of the Illinois Power Generating Company and local emergency responders. This meeting may be in the form of a face-to-face meeting, tabletop exercise, or additional training regarding the EAP.

Table 5-1. Emergency Supplies and Equipment

Item	On-site (Yes/No/Occasionally)	Remarks
Flashlights	Yes	Contact Shift Supervisor(s) for location and availability.
Generator	Yes	Contact Shift Supervisor(s) for location and availability.
Extension Cords	Yes	Contact Shift Supervisor(s) for location and availability.
Fire extinguishers	Yes	Contact Shift Supervisor(s) for location and availability.
Floodlights	Yes	Contact Shift Supervisor(s) for location and availability.
Backhoe		Contact Shift Supervisor(s) for location and availability.
Dozer	Yes	CAT D10R + CAT D9R
Large Equipment (Rental – including excavating equipment, pumps, lighting)		Contact Shift Supervisor(s) for location and availability.
Grader	Yes	CAT 14H
Track Hoe Excavator	Yes	CAT 330L
Scraper	Yes	637D Coal Scraper
Dump Truck	Yes	CAT 730 (30 Ton)
Pump and Hoses	Yes	Contact Shift Supervisor(s) for location and availability.
Sandbags and Sand		Contact Shift Supervisor(s) for location and availability.
Fill (Stone, aggregate, sand)	Yes	Contact Shift Supervisor(s) for location and availability.
Concrete/grout	No	Contact Shift Supervisor(s) for location and availability.
Geotextile Filter Fabric	Yes	2 rolls of 10-ounce, non-woven filter fabric (stock #4906798)
Plastic Sheeting		Contact Shift Supervisor(s) for location and availability.
Rope	Yes	Contact Shift Supervisor(s) for location and availability.
Personal Flotation Devices	Yes	Contact Shift Supervisor(s) for location and availability.

Table 5-2. Supplier Addresses

Supply / Rental Item(s)	Supplier Contact Information	Distance from Site (miles)	Address
Sandbags	NYP Corp.	125	1416 North Broadway, St. Louis, MO. 63102 800-331-2445 800-524-1052 (emergency)
Gravel, Sand, & Riprap	C & H Gravel	27	1682 Co. Rd. 1050 N., Greenup, IL 62428 (217) 849-2323
	Lawrence Gravel Inc.	41	Palestine, IL 62451 (618) 586-5433
Cement, Sand, Grout	Newton Ready-Mix Division	11	8560 IL-360, Newton, IL 62448 (618) 783-8611
Portable Pumps, Rental Equipment	Jensen Equipment Company	19	Newton, Illinois (888) 826-2048
	JJet Rental-Sales & Service	39	905 IL-49, Casey, IL 62420 (217) 932-9033
	RWCI Equipment Sales, Rentals & Services	32	10 Industrial Park, Flora, IL 62839 (618) 662-8941
	Senco Construction Inc.	36	1408 S. Eaton St., Robinson, IL 62454 (618) 546-1485
	Bahrns Equipment	23	1708 S. Banker St., Effingham, IL 62401 (217) 342-2909
Large Capacity Portable Pumps	Xylem / Godwin Pumps Mine Supply Co.	87	1703 Shawnee St., Mt. Vernon, IL 62864 (618) 242-2087
	Water Movers Equipment Rental	125	1800 S. 3rd Street, St. Louis, MO 63104 (636) 717-2220
General Hardware & Supply	Kirchner Building Center	11	401 E. Decatur St., Newton, IL 62448 (618) 783-2388
	Hurn Lumber Company	30	200 W. Butler St., Olney, IL 62450 (618) 395-8576

6 FACILITY / IMPOUNDMENT DESCRIPTION

The impoundment included in this EAP is described as follows and illustrated in Figure 1-2. Table 6-1 contains additional geometric details for the impoundment.

The Newton Power Plant is located on the west bank of Newton Lake in South Muddy Township, Jasper County, Illinois. The Power Plant is located approximately eight miles southwest of the Town of Newton, Illinois.

Primary Ash Pond: A diked earthen impoundment that extends over an area of approximately 400 acres. The crest of the impoundment is about 15 foot wide at an approximate elevation of 555.0 feet with an average adjacent ground elevation outside of the impoundment of about 530.0 feet. The pond has an operating pool about 268.8 acres in size, which currently has a water surface elevation of about 533.5 feet (the interior base of the pond is partially incised). The Primary Ash Pond discharges to the southwest through a concrete control structure to the Secondary Pond.

Table 6-1. Power Plant Impoundment Characteristics

Feature/Parameter	Primary Ash Pond
Maximum Embankment Height	42 feet
Length of Dam	16,600 feet
Crest Width	15 feet
Crest Elevation	554.0 feet
Reservoir Area at Top of Dam	400 acres
Storage Capacity at Top of Dam	9250 acre-feet
Primary Spillway Type	30-inch Coated CMP w/ Concrete Weir Box w/ Stop Logs
Primary Spillway Crest Elevation	533.5 feet
Storage Capacity at Primary Spillway Elevation	1753 acre-feet
Reservoir Area at Normal Water Surface Elevation	162.0 acres
Auxiliary Spillway Type	Secondary Weir Structure
Auxiliary Spillway Crest Elevation	536.0 feet

7 BREACH INUNDATION MAP AND POTENTIAL IMPACTS

An inundation map for a potential breach scenario of the Primary Ash Pond is provided as Figure 7-1. It is the Jasper County ESDA/EMA's responsibility to keep a current list of affected parties/properties to contact in the case of emergencies that result in Response Level 2 or 3. This list should encompass all properties within and adjacent to the probable inundation extents shown in the provided map.

The methodology used to identify probable inundation extents for potential breach scenarios varied as a function of the impoundment size, location, surrounding topography, and surrounding structures/facilities/waterbodies.

The methodology used to identify probable inundation extents for the Primary Ash Pond consisted of a visual assessment performed by comparing pond and embankment elevations to surrounding topography using LIDAR elevation data obtained from the Illinois Height Modernization Program. Additionally, an approximate volumetric comparison was evaluated to determine a potential breach of the Primary Ash Pond would not result in an immediate and significant rise in water surface elevations on Newton Lake.

The approximate inundation area is illustrated in Figure 7-1.

Legend

☐ CCR Surface Impoundment Boundary

🟦 Expected Breach Inundation Area

0 0.5 1 Miles

1:31,680 (1" = 0.5 miles at original document size of 11x17)

Stantec DYNEGY

Project Location
Latitude: 38.936621
Longitude: -88.277038
Jasper County, Illinois

175666013
Prepared by EC on 2017-03-08
Technical Review by TS on 2017-03-27
Independent Review by MM on 2017-03-20

Client/Project
Newton Power Station
Emergency Action Plan

Figure No.
7-1

Title
Inundation Map
Primary Ash Pond

Notes

1. Coordinate System: WGS 1984 Web Mercator Auxiliary Sphere
2. Basemap Source: Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community
3. Impoundment Boundaries Provided by Client (Dated 9/9/2015)

ATTACHMENT G

CCR Fugitive Dust Control Plan

for

Newton Power Plant

Prepared for:

Illinois Power Generating Company

Newton Power Plant
6725 North 500th Street
Newton, IL 62448

Prepared by:

Burns & McDonnell
Kansas City, Missouri

Amendment 1

October 2021

Table of Contents

List of Tables

1 Introduction

This Coal Combustion Residuals (CCR) fugitive dust control plan has been prepared for the Newton Power Plant, located in Jasper County, Illinois. This plan addresses the air criteria in 40 C.F.R. § 257.80 of the United States Environmental Protection Agency's CCR rule, which requires the owner or operator of a CCR unit to "adopt measures that will effectively minimize CCR from becoming airborne at the facility" and to "prepare and operate in accordance with a CCR fugitive dust control plan." The plan also addresses the air criteria in 35 I.A.C. 845.500 of the Illinois Environmental Protection Agency's CCR rule which contains similar requirements to the federal CCR rule.

1.1 Facility Information

- Facility Name: Newton Power Plant
- Facility Address: 6725 North 500th Street, Newton, IL 62448
- Owner/Operator: Illinois Power Generating Company

1.2 Certification

The owner or operator must obtain a certification from a qualified professional engineer that the initial CCR fugitive dust control plan, or any subsequent amendment of it, meets the requirements of 40 C.F.R. § 257.80 and 35 I.A.C. 845.500. See 40 C.F.R. § 257.80(b)(7); 35 I.A.C. 845.500(b)(7).

I certify under penalty of law that, to the best of my knowledge, this plan meets the requirements of 40 C.F.R. § 257.80 and 35 I.A.C. 845.500. This certification is based on my review of the document and conditions at the site and on my inquiry of the person or persons who managed the preparation of this document.

John R. Hesemann
Printed Name of Qualified Professional Engineer

9/09/2021
Signature of Qualified Professional Engineer and Date

062.058523 – Illinois – Expires 11/30/2021
Registration Number and State

JOHN ROBERT HESEMANN
062-058523

2 CCR Fugitive Dust Control Measures and Appropriateness

CCR fugitive dust has the potential to become airborne at the facility during periods of CCR management in the CCR units, CCR handling and CCR transport. Areas at the facility that have the potential for airborne CCR fugitive dust are CCR surface impoundments, a CCR landfill, CCR handling equipment and CCR transport in trucks. This section identifies and describes the control measures selected and adopted by the facility to minimize CCR from becoming airborne at the facility and explains how the selected measures are applicable and appropriate for site conditions. The control measures may be adjusted or modified based on observed effectiveness of minimizing CCR from becoming airborne and weather conditions.

2.1 Management of CCR in the CCR Units

The facility manages CCR in a surface impoundment and landfill located at the facility. Table 2-1 below identifies CCR fugitive dust control measures that have been selected for use by the facility during CCR management in the CCR units, including placement of CCR into the CCR unit, and explains how the selected measures are applicable and appropriate for site conditions. The facility will use the identified measures during CCR management in the CCR units to minimize CCR from becoming airborne at the facility.

CCR Activity	CCR Fugitive Dust Control Measure	Applicability and Appropriateness of Control Measure
Management of CCR in the facility's CCR units	Condition CCR to be emplaced in the landfill before loading into vehicles for transport to the landfill.	Conditioning CCR to be placed in the landfill allows CCR to bind together and thus minimizes the potential for CCR fugitive dust generation when CCR is managed in the landfill. The added moisture content will prevent wind dispersal of the CCR but will not result in free liquids.
	Apply cover to exposed material in the landfill.	Applying approved cover material, such as conditioned fly ash, minimizes wind entrainment of CCR material.
	Wet management of CCR bottom ash and CCR fly ash in CCR surface impoundments.	Wet management of CCR minimizes the potential for CCR fugitive dust generation.
	Water areas of exposed CCR in CCR units, as necessary.	Water will be applied to areas of exposed CCR to maintain moisture content to minimize the potential for CCR fugitive dust generation in excessively dry or windy conditions. Wetting activities will not generate “free liquids” within the landfill.
	Naturally occurring grass vegetation in areas of exposed CCR in CCR surface impoundments.	Vegetation provides a wind screen and/or cover and reduces wind entrainment of CCR.
	Reduce or halt operations during high wind events, as necessary.	Reducing or halting operations during high wind events minimizes the potential for CCR fugitive dust generation.

Table 2-1. Control Measures for CCR Management in CCR Units

2.2 Handling of CCR

CCR is regularly removed from the boiler system and conveyed to the CCR handling system, which includes silos and truck loading areas. CCR fly ash is pneumatically conveyed in an enclosed system from the precipitator hoppers to storage silos. CCR bottom ash and CCR fly ash are wet sluiced into CCR surface impoundments. Prior to transport, dry fly ash is loaded into trucks from CCR fly ash silos utilizing a telescoping chute. When unloading the CCR fly ash silos for transport to and emplacement in the CCR landfill, a mixer is used to condition the CCR fly ash as it is loaded into trucks. Table 2-2 below identifies CCR fugitive dust control measures that have been selected for use by the facility during handling of CCR and explains how the selected measures are applicable and appropriate for site conditions. The facility will use the identified measures when handling CCR to minimize CCR from becoming airborne at the facility.

CCR Activity	CCR Fugitive Dust Control Measure	Applicability and Appropriateness of Control Measure
Handling of CCR at the facility	Wet sluice CCR bottom ash and fly ash to CCR surface impoundments.	Wet sluicing CCR minimizes the potential for CCR fugitive dust generation.
	Pneumatically convey dry CCR fly ash to storage silos in an enclosed system.	Conveying CCR fly ash in an enclosed system minimizes the potential for CCR fugitive dust generation.
	Condition CCR fly ash to be emplaced in the landfill before loading it into trucks for transport to the landfill.	Conditioning allows CCR to bind together and thus minimizes the potential for CCR fugitive dust generation while loading CCR into trucks (and during transport and emplacement in the landfill).
	Condition CCR materials to be transported offsite before they are loaded into trucks, as necessary.	Conditioning allows CCR to bind together and thus minimizes the potential for CCR fugitive dust generation while loading CCR into trucks (and during transport and emplacement in the landfill).
	Load CCR transport trucks from the CCR fly ash silos in a partially enclosed area.	Partial enclosure of the CCR transport truck loading area reduces the potential for wind to cause CCR fugitive dust to become airborne.
	Load CCR transport trucks from the CCR fly ash silos using a telescoping chute, when applicable.	Use of a telescoping chute while loading dry CCR fly ash reduces the drop height from the end of the chute into the truck and minimizes the potential for CCR fugitive dust to become airborne.
	Perform housekeeping, as necessary, in the fly ash loading area.	Good housekeeping measures, such as sweeping or wetting the loading area, minimizes the potential for CCR fugitive dust generation during handling activities.
	Operate fly ash handling system in accordance with good operating practices.	Operation in accordance with good operating practices minimizes the potential for CCR fugitive dust generation.
	Maintain and repair as necessary dust controls on the fly ash handling and truck load-out system.	Performing maintenance and repairs as needed to maintain dust controls in good operating condition minimizes the potential for CCR fugitive dust generation.
	Reduce or halt operations during high wind events, as necessary.	Reducing or halting operations during high wind events minimizes the potential for CCR fugitive dust generation.

Table 2-2. Control Measures for Handling CCR

2.2.1 Conditioning of CCR Prior to Emplacement in CCR Landfill

Conditioned CCR is CCR that has been wetted with water or an appropriate chemical dust suppressant. Water or a chemical dust suppressant is added to raise the moisture content of the CCR to prevent wind dispersal but will not result in free liquids. Conditioning allows for the CCR to bind together, which minimizes the potential for CCR fugitive dust.

All CCR generated on site that is placed into the facility’s landfill, as well as CCR generated offsite that is authorized for placement in the facility’s landfill, is conditioned in a mixer or otherwise conditioned prior to loading into trucks for transport to the landfill. Therefore, all CCR that is added to the facility’s landfill is emplaced in the landfill as conditioned CCR.

2.3 Transportation of CCR

CCR is transported via truck at the facility using unpaved facility roads. Table 2-3 below identifies CCR fugitive dust control measures that have been selected for use by the facility during transport of CCR. The facility will use the identified measures when transporting CCR to minimize CCR from becoming airborne at the facility.

CCR Activity	CCR Fugitive Dust Control Measure	Applicability and Appropriateness of Control Measure
Transportation of CCR at the facility	Condition CCR to be emplaced in the landfill before loading it into vehicles for transport to the landfill.	Conditioning CCR increases moisture content of the CCR and minimizes the potential for CCR fugitive dust generation during CCR transport (and emplacement in the landfill).
	Condition CCR materials to be transported offsite before they are loaded into trucks, as necessary.	Conditioning allows CCR to bind together and thus minimizes the potential for CCR fugitive dust generation while loading CCR into trucks and during transport.
	Cover or enclose trucks used to transport CCR material, as necessary.	Covering or enclosing trucks transporting CCR on facility CCR haul roads minimizes the potential for CCR fugitive dust generation from the CCR transport trucks.
	Limit the speed of vehicles to no more than 15 mph on facility roads.	Limiting the speed of vehicles traveling on facility roads minimizes the potential for CCR fugitive dust generation from the CCR transport trucks.
	Sweep or rinse CCR off of the outside of the trucks transporting CCR, as necessary.	Removing CCR present on the outside of the truck minimizes the potential for movement of the truck or wind to cause CCR fugitive dust to become airborne.
	Remove CCR, as necessary, deposited on facility road surfaces during transport.	Removing CCR deposited on facility road surfaces as a result of transport minimizes the potential for CCR fugitive dust generation from vehicle traffic.
	Condition CCR haul roads with water or dust suppressant, as necessary.	Watering CCR haul roads minimizes the potential for dust generation to occur as a result of CCR hauling traffic and heavy equipment use.
	Reduce or halt operations during high wind events, as necessary.	Reducing or halting operations during high wind events minimizes the potential for CCR fugitive dust generation.

Table 2-3. Control Measures for Transportation of CCR

3 Procedures for Periodic Assessment of Effectiveness of the Plan

The facility conducts inspections associated with CCR fugitive dust control. The facility also uses the procedures identified in section 5 of this plan to log every citizen complaint involving CCR fugitive dust events at the facility. These inspections and the investigations of citizen complaints will be used to periodically assess the effectiveness of the CCR fugitive dust control plan per 40 C.F.R. § 257.80(b)(4) and 35 I.A.C. 845.500(b)(3).

The facility routinely performs inspections to verify the effectiveness of the CCR fugitive dust control measures used at the facility. Inspections are conducted during daylight working hours and include observing for the presence of CCR fugitive dust emissions from vehicles transporting CCR on facility roads, CCR handling and CCR management activities, including CCR placement in CCR units. Inspection records include information such as the name of the person conducting the inspection, the date and time of the inspection, the results of the inspection, and any corrective action taken.

When a CCR fugitive dust event is observed or a citizen complaint involving a CCR fugitive dust event at the facility is received, current CCR management practices will be reviewed to see that the selected control measures are being properly implemented. If the control measures are not being properly implemented, relevant operating personnel will be notified and, as warranted, re-trained in the proper implementation of CCR fugitive dust control measures. If appropriate, use of revised and/or additional control measures will be evaluated. As warranted, revised and/or additional control measures found to be applicable and appropriate to control CCR fugitive dust emissions will be incorporated into an amended CCR fugitive dust control plan.

The plan also will be reassessed in the event of material changes in site conditions potentially resulting in CCR fugitive dust becoming airborne at the facility.

4 Recordkeeping, Notification, Internet Site

The written CCR fugitive dust control plan, any amendment of the written plan, and the annual CCR fugitive dust control report required by 40 C.F.R. § 257.80(c) and 35 I.A.C. 845.500(c) will be placed in the facility's written operating record and posted to the company's CCR website in accordance with 40 C.F.R. § 257.105(g), § 257.107(g) and 845.800(d)(7), (14) and 845.810(e). Notification of the availability of the CCR fugitive dust control plan, any amendment of the plan, and the annual CCR fugitive dust control report will be provided to IEPA in accordance with 40 C.F.R. § 257.106(g). Any amendment of the fugitive dust control plan will be submitted to IEPA in accordance with 845.500(b)(5).

Additionally, pursuant to 845.500(b)(6), this fugitive dust control plan is being placed in facility's operating record and posted to the company's CCR website prior to the submission of any permits for the Newton Power Plant.

5 Procedures to Log Citizen Complaints

In the event the owner or operator of the facility receives a citizen complaint involving a CCR fugitive dust event at the facility, relevant information about the complaint will be logged. Information that will be recorded includes, as applicable:

- Date/Time the complaint is received
- Date/Time and duration of the CCR fugitive dust event
- Description of the nature of the CCR fugitive dust event
- Name of the citizen entering the complaint
- Address & phone number of citizen entering the complaint
- Name of the personnel who took the complaint
- All actions taken to assess and resolve the complaint

All citizen complaints involving CCR fugitive dust events at the facility will be investigated promptly. As deemed appropriate or necessary, corrective measures will be taken and a follow-up response will be provided to the complainant.

Pursuant to 35 I.A.C. 845.500(b)(2), quarterly reports will be submitted to IEPA no later than 14 days from the end of the quarter for all complaints received in that quarter. At a minimum, the quarterly report will include the date of the complaint, the date of the complainant (if given), and all actions taken to assess and resolve the complaint.

6 Amendments

The written CCR fugitive dust control plan may be amended at any time provided the revised plan is placed in the facility's operating record as required by 40 C.F.R. § 257.105(g)(1) and 845.500(b)(6). Any amendment of the fugitive dust control plan will be submitted to IEPA in accordance with 845.500(b)(5). The written CCR fugitive dust control plan must be amended whenever there is a change in conditions that would substantially affect the written plan in effect.

Amendment Number and Date	Pages or Section	Description of Amendment	Professional Engineer Certifying Plan
Version 0 October 2015	--	Initial Plan	Wendy M. Pennington
Amendment 1 October 2021	Various	Administrative changes and adjustments to site condition controls as appropriate.	John R. Hesemann

Table 6-1. CCR Fugitive Dust Control Plan Amendments

ATTACHMENT H

Intended for
Illinois Power Generating Company

Date
October 25, 2021

Project No.
1940100806-008

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT

PRIMARY ASH POND
NEWTON POWER PLANT
NEWTON, ILLINOIS

RAMBOLL Bright ideas. Sustainable change.

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT NEWTON POWER PLANT PRIMARY ASH POND

Project Name	**Newton Power Plant Primary Ash Pond**
Project No.	**1940100806-008**
Recipient	**Illinois Power Generating Company**
Document Type	**Hydrogeologic Site Characterization Report**
Revision	**FINAL**
Date	**October 25, 2021**

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Hydrogeologist

Nathaniel R. Keller
Senior Hydrogeologist

CONTENTS

TABLES (WITHIN TEXT)

TABLES (ATTACHED)

FIGURES

APPENDICES

ACRONYMS AND ABBREVIATIONS

°F	degrees Fahrenheit
§	Section
35 I.A.C.	Title 35 of the Illinois Administrative Code
40 C.F.R.	Title 40 of the Code of Federal Regulations
CCR	coal combustion residuals
cm/s	centimeters per second
CSM	conceptual site model
bgs	below ground surface
ESRI	Environmental Systems Research Institute
ft/day	feet/day
ft/ft	feet per feet
ft/mi	feet per mile
g	horizontal acceleration
GMP	Groundwater Monitoring Plan
GWPS	Groundwater Protection Standard
HCR	Hydrogeologic Site Characterization Report
HMP	Hydrogeologic Monitoring Plan
HUC	Hydraulic Unit Code
ID	identification
IDNR	Illinois Department of Natural Resources
IEPA	Illinois Environmental Protection Agency
ILWATER	ISGS Illinois Water and Related Wells
IPGC	Illinois Power Generating Company
ISGS	Illinois State Geological Survey
ISWS	Illinois State Water Survey
LCU	Lower Confining Unit
LF 1	Phase 1 Landfill
LF 2	Phase 2 Landfill
LVW	Low Volume Wastewater
mg/L	milligrams per liter
NAVD88	North American Vertical Datum of 1988
NID	National Inventory of Dams
No.	number
NPDES	National Pollutant Discharge Elimination System

NPP	Newton Power Plant
NRT	Natural Resource Technology, Inc.
OBG	O'Brien and Gere Engineers, Inc.
PAP	Primary Ash Pond
Part 845	Standards for the Disposal of Coal Combustion Residuals in Surface Impoundments: Title 35 of the Illinois Administrative Code § 845
pcf	pounds per cubic foot
pCi/L	picocuries per liter
PMP	Potential Migration Pathway
PWS	Public Water Supply
Ramboll	Ramboll Americas Engineering Solutions, Inc.
Rapps	Rapps Engineering and Applied Science
RCRA	Resource Conservation and Recovery Act of 1976
SI	surface impoundment
Site	Primary Ash Pond
SSURGO	Soil Survey Geographic
SU	standard units
TDS	total dissolved solids
UCU	upper confining unit
UD	upper drift
USEPA	United States Environmental Protection Agency
USCS	Unified Soil Classification System
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey

EXECUTIVE SUMMARY

This Hydrogeologic Site Characterization Report (HCR) for the Primary Ash Pond (PAP) at Newton Power Plant (NPP) expands upon the hydrogeology, groundwater quality data, and conceptual site model (CSM) presented in previous hydrogeologic investigation reports prepared for the PAP. This report has been assembled to satisfy the information and analysis requirements of Title 35 of the Illinois Administrative Code (35 I.A.C.) Section (§) 845.620 as summarized in **Table ES-1**. The CSM includes hydrogeologic and groundwater quality data specific to the PAP, which has been collected between 2015 and 2021. The PAP (Vistra identification [ID] number [No.] 501, Illinois Environmental Protection Agency [IEPA] ID No. W0798070001-01, and National Inventory of Dams [NID] No. IL50719) is located at the NPP which is located in Newton, Illinois (**Figure 1-1**).

The PAP is located south of the power plant and situated in a predominantly agricultural area. The PAP is surrounded by Newton Lake on the west, south, and east. Beyond the lake is additional agricultural land. Three coal combustion residuals (CCR) units are present on the NPP property, including the PAP and two landfills: the Phase 1 Landfill (LF 1) is located northwest and west of the PAP, and the Phase 2 Landfill (LF 2) is located west of the PAP. The PAP is located in Section 26 and the western half of Section 25, Township 6 North, Range 8 East.

In addition to the CCR present in the PAP, there are six layers of unlithified material present above the bedrock, these materials were categorized into four hydrostratigraphic units in this report, presented below in descending order:

- **Upper Drift (UD) / Potential Migration Pathway (PMP):** The UD is composed of the low permeability silts and clays of the Peoria Silt and Sangamon Soil and the sandier soils of the Hagarstown Member (*i.e.,* PMP).
  - **Hagarstown Member / PMP:** The Hagarstown Member consists of discontinuous sandier deposits of the UD, where present, and overlies the Vandalia Till.
- **Upper Confining Unit (UCU):** This unit consists of the low permeability clay and silt of the Vandalia Till.
- **Uppermost Aquifer:** This unit is composed of the Mulberry Grove Formation, which onsite has been classified as poorly graded sand, silty sand, clayey sand, and gravel.
- **Lower Confining Unit (LCU):** This unit is comprised of low permeability silt and clay of the Smithboro Till (Smithboro Till) and the Banner Formation.

Groundwater migrates downward through the UD and UCU into the uppermost aquifer. Groundwater in the uppermost aquifer flows from north to south/southwest and converges near a former drainage feature located west of the PAP. Groundwater elevations vary seasonally, although generally less than one foot per year. The surface water elevation at Newton Lake (at location SG02) measured between February 15 and March 9, 2021 ranged from 504.42 to 504.84 feet North American Vertical Datum of 1988 (NAVD88). Groundwater elevations in the uppermost aquifer at downgradient wells were observed around 491 feet NAVD88 (approximately 15 feet lower than the Lake elevation). The separation between measured groundwater elevations and Lake elevations (and observed downward vertical gradients) indicates groundwater does not flow into Newton Lake from the uppermost aquifer.

Part 845 parameters were monitored in uppermost aquifer and PMP monitoring wells as part of groundwater quality evaluations performed between 2015 and present. These data were supplemented with installation and sampling of additional locations in 2021. The results indicate that the following parameters were detected at concentrations greater than the applicable 35 I.A.C. § 845.600 groundwater protection standards (GWPSs) and are considered potential exceedances:

- Arsenic at six uppermost aquifer wells, including downgradient wells APW08, APW09, APW15, and APW16 and background wells APW05 and APW06.
- Chloride at upgradient UD well APW05S and downgradient uppermost aquifer well APW15.
- Cobalt at PMP well APW12.
- Fluoride at downgradient uppermost aquifer well APW15 and APW18.
- Lead at downgradient uppermost aquifer wells APW08, APW11, and APW18.
- Lithium at three PMP wells APW02, APW04, and APW12; one upgradient UD well APW05S; and two downgradient uppermost aquifer wells APW13 and APW14.
- pH values below the lower range of the GWPS were observed at four PMP wells APW02, APW03, APW04, APW12; one background UA well APW06; and two downgradient uppermost aquifer wells APW11 and APW13.
- Radium 226 and 228 combined at downgradient uppermost aquifer well APW16.
- Sulfate at three PMP wells APW02, APW04, and APW12; one upgradient UD well APW05S; and one downgradient uppermost aquifer well APW10
- Thallium at one background well APW06, and two downgradient uppermost aquifer wells APW11 and APW18.
- Total dissolved solids (TDS) at four PMP wells APW02, APW03, APW04, and APW12; and one upgradient UD well APW05S.

Concentration results for the above parameters were compared directly to 35 I.A.C. § 845.600 GWPS to determine potential exceedances. Potential exceedances include results reported during the background groundwater monitoring or prior period that are greater than the GWPS. The results are considered potential exceedances because the results were compared directly to the standard and did not include an evaluation of background groundwater quality and the statistical methodologies proposed in the groundwater monitoring plan (GMP) provided in the Operating Permit application. Exceedances will be determined following IEPA approval of the GMP.

TABLE ES-1. PART 845 REQUIREMENTS CHECKLIST

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, ILLINOIS

Part 845 Reference	Part 845 Components	Location of Information in HCR
845.620(b)	**The hydrogeologic site characterization shall include but not be limited to the following:**	--
845.620(b)(1)	Geologic well logs/boring logs;	Table 3-1 Figure 3-1 Appendix C
845.620(b)(2)	Climatic aspects of the site, including seasonal and temporal fluctuations in groundwater flow;	Sections 3.2.4 & 3.3.1 Figures 3-3 to 3-4
845.620(b)(3)	Identification of nearby surface water bodies and drinking water intakes;	Sections 3.3.2 & 5.2 Appendix B
845.620(b)(4)	Identification of nearby pumping wells and associated uses of the groundwater;	Section 5.1 Appendix B
845.620(b)(5)	Identification of nearby dedicated nature preserves;	Section 5.3 Appendix B
845.620(b)(6)	Geologic setting;	Section 2 Figures 2-1 to 2-5
845.620(b)(7)	Structural characteristics;	Section 2.4.3 Figure 2-4
845.620(b)(8)	Geologic cross-sections;	Figures 2-6 through 2-8
845.620(b)(9)	Soil characteristics;	Section 2.3 Figure 2-2 Tables 2-1 & 2-4

TABLE ES-1. PART 845 REQUIREMENTS CHECKLIST

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, ILLINOIS

Part 845 Reference	Part 845 Components	Location of Information in HCR
845.620(b)(10)	Identification of confining layers;	Section 3.2.1
845.620(b)(11)	Identification of potential migration pathways;	Section 3.2.1
845.620(b)(12)	Groundwater quality data;	Section 4.2 Table 4-1
845.620(b)(13)	Vertical and horizontal extent of the geologic layers to a minimum depth of 100 feet below land surface, including lithology and stratigraphy;	Section 2.5 Figures 2-6 to 2-8
845.620(b)(14)	A map displaying any known underground mines beneath a CCR surface impoundment;	Section 2.4.5 Appendix B
845.620(b)(15)	Chemical and physical properties of the geologic layers to a minimum depth of 100 feet below land surface;	Section 2.5 Tables 2-1, 2-2, & 2-4 Appendix E
845.620(b)(16)	Hydraulic characteristics of the geologic layers identified as migration pathways and geologic layers that limit migration, including:	Sections 3.2.4.1, 3.2.5, & 3.2.6 Tables 3-2 to 3-4 Appendix F
845.620(b)(16)(A)	water table depth;	Section 3.2.4 Figures 3-3 & 3-4
845.620(b)(16)(B)	hydraulic conductivities;	Section 3.2.5 Table 3-3 Appendix F

TABLE ES-1. PART 845 REQUIREMENTS CHECKLIST
HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, ILLINOIS

Part 845 Reference	Part 845 Components	Location of Information in HCR
845.620(b)(16)(C)	effective and total porosities;	Section 2.5 Table 2-1
845.620(b)(16)(D)	direction and velocity of groundwater flow; and	Sections 3.2.4 & 3.2.6 Tables 3-2 & 3-4 Figures 3-3 & 3-4
845.620(b)(16)(E)	map of the potentiometric surface;	Figures 3-3 & 3-4
845.620(b)(17)	Groundwater classification pursuant to 35 I.A.C. § 620	Section 3.2.7

[O: EDP 08/23/21, U: SSW 9/1/21, C: LDC 09/21/21]

Notes:
35 I.A.C. § 620 = Title 35 of the Illinois Administrative Code, Part 620
HCR = Hydrogeologic Characterization Report
-- = reference to main regulation

1. INTRODUCTION

1.1 Overview

In accordance with requirements of the Standards for the Disposal of Coal Combustion Residuals in Surface Impoundments (SIs): 35 I.A.C. § 845 (Part 845) (IEPA, April 15, 2021), Ramboll Americas Engineering Solutions, Inc. (Ramboll) has prepared this HCR on behalf of NPP (**Figure 1-1**), operated by Illinois Power Generating Company (IPGC). This report will apply specifically to the CCR Unit referred to as the PAP. However, information gathered to evaluate other CCR units at the NPP regarding geology, hydrogeology, and groundwater quality is included, where appropriate. The PAP is a 404-acre unlined CCR SI used to manage stormwater runoff, bottom ash, fly ash, low-volume wastewater (LVW) from the plant's two coal-fired boilers. The PAP discharges into the Secondary Pond, which is used to clarify process water prior to discharge in accordance with the plants National Pollutant Discharge Elimination System (NPDES) permit (No. IL0049191) at the NPP. This HCR includes Part 845 content requirements specific to 35 I.A.C. § 845.620(b) (Hydrogeologic Site Characterization) for the PAP at NPP.

1.2 Part 845 Description

CCR is commonly referred to as coal ash, and CCR SIs are commonly referred to as coal ash ponds. Part 845 contains comprehensive rules for the design, construction, operation, corrective action, closure, and post closure care of these SIs. This rule includes GWPSs applicable at the waste boundary at each CCR SI and requires each owner or operator to monitor groundwater. IEPA's rule includes a permitting program as well as all federal standards for CCR SIs promulgated by the United States Environmental Protection Agency (USEPA). In addition, IEPA's rule includes procedures for public participation, closure alternatives analyses, and closure prioritization, and provides access to records via public website. The rules also include financial assurance requirements for CCR SIs.

A checklist which identifies the specific requirements of 35 I.A.C. § 845.620 is included in **Table ES-1**. The table provides references to sections, tables, and figures included in this document to locate the information that meets specific requirements of 35 I.A.C. § 845.620.

1.3 Previous Investigations and Reports

Numerous hydrogeologic investigations have been performed concerning the CCR Units located at the NPP. The information presented in this HCR includes comprehensive data collection and evaluations from prior hydrogeologic investigation reports (most recent to oldest), including, but not limited to, the following:

- ***Hanson, 2019, Phase 1 Ash Landfill Annual Report, Newton Power Station, Jasper County, Illinois.*** An annual report to provide groundwater and leachate monitoring results for 2019 and proposed activities for 2020, pursuant to 35 I.A.C. § 813.504 and Permit Condition III. Report includes monitoring data, graphical results, and a summary of modifications or changes to the monitoring program.
- ***O'Brien & Gere Engineers, Inc. (OBG), 2017, Hydrogeologic Monitoring Plan, Newton Power Station, Canton, Illinois.*** Although the title refers to Canton, Illinois, the subject of the report is the NPP. The Hydrogeologic Monitoring Plan (HMP) was prepared to provide background information necessary to support the monitoring well network established for development of the Sampling and Analysis Plan requirements of the USEPA Final Rule to

regulate the disposal of CCR as solid waste under Subtitle D of the Resource Conservation and Recovery Act of 1976 (RCRA) for the NPP. The HMP provides site geology and hydrogeology, aquifer properties, and monitoring network placement and rationale.

- ***AECOM, 2016, History of Construction, Newton Power Station, Newton, Illinois.*** This is a construction history compiled to fulfill Title 40 of the Code of Federal Regulations (40 C.F.R.) § 257.73(c)(1), which requires that the owner/operator of an existing CCR SI that either (1) has a height of five feet or more and a storage volume of 20 acre-feet or more, or (2) has a height of 20 feet or more, compile a history of construction that contains, to the extent feasible, the information specified in 40 C.F.R. § 257.73(c)(1)(i) through (xii). The history of construction was based on existing documentation; AECOM's document review included record drawings, geotechnical investigations, etc., for the PAP.
- ***Natural Resource Technology, Inc. (NRT), April 10, 2013, Hydrogeological Assessment Report, Revision 1, Newton Energy Center, Jasper County, Illinois.*** In 2009, Ameren (the former owner/operator) commissioned a hydrogeologic study, water well survey, development of a GMP, and an initial groundwater quality assessment. This report summarizes hydrogeologic information pertinent to the Site, evaluates groundwater quality data to determine if groundwater has been affected adversely, and determines the potential for off-site migration and for potential groundwater receptors in the event of such a migration.
- ***Geotechnology, Inc., February 8, 2011, Initiation of Monitoring Report, Ameren, Newton Power Station, Newton, Illinois.*** This report documents the results of the monitoring well installation and groundwater monitoring activities performed at the Site. Three wells were installed, developed, and sampled.
- ***Rapps Engineering and Applied Science (Rapps), November 2009, Site Characterization and Groundwater Monitoring Plan for CCP Impoundment, Ameren Energy Generating Company, Newton Power Station, Jasper County, Illinois.*** Hydrogeologic study and GMP to assess the potential for constituent migration from this impoundment. Includes an assessment of subsurface hydrogeologic conditions at the Site, identification of private, potable water wells and oil and gas wells within 2,500 feet of the facility, public water supply (PWS) wells within 10 miles of the facility, and plans for a groundwater monitoring well network designed to characterize and monitor groundwater quality.
- ***Rapps, 1997, Hydrogeologic Investigation and Groundwater Monitoring Program, Newton Power Station, Jasper County, Illinois.*** Investigation presents site-specific data obtained through the completion of approximately 40 borings, 20 monitoring wells, and review of regional information and an evaluation of subsurface data from nearby residential wells. Part of Application for Landfill Permit.

A GMP is being prepared for the PAP in conjunction with this report and is included in the Operating Permit to which this Report is attached.

1.4 Site Location and Background

The NPP is located in Jasper County in the southeastern part of central Illinois, approximately seven miles southwest of the town of Newton (**Figure 1-1**). The PAP is located in Section 26 and the western half of Section 25, Township 6 North, Range 8 East. The PAP is located south of the power plant and situated in a predominantly agricultural area. The PAP is surrounded by Newton Lake on the west, south, and east. Beyond the lake is additional agricultural land. LF 1 is located northwest and west of the PAP, and LF 2 is located west of the PAP (**Figure 1-2**). The PAP is the subject of this report and will hereafter be referred to as the Site in this document.

1.5 Site History and Unit Description

The PAP was constructed in 1977 and has a design capacity of approximately 9,715 acre-feet. There is also a non-CCR 83.6 acre-feet Secondary Pond located immediately south of the PAP. The PAP has a surface area of 404 acres and the Secondary Pond has an area of 9.3 acres. The PAP currently receives bottom ash, fly ash, and LVW from the plant's two coal-fired boilers. The SI is operated per NPDES Permit No. IL0049191, Outfall 001 (located at the Secondary Pond). Areas within the impoundment were excavated during construction for native materials used to build the containment berms. In 2014, three areas along the interior berm were re-graded and covered with riprap (AECOM, 2016).

2. REGIONAL AND LOCAL GEOLOGY

2.1 Topography

The embankments surrounding the PAP are at an elevation of approximately 550 feet NAVD88 (**Figure 2-1**) with the surrounding areas, Newton Lake, generally at an elevation of around 504 to 505 feet NAVD88. Topographic maps drawn prior to construction indicate the area of the PAP was generally between 500 and 550 feet NAVD88, except for the drainage features in the south-central portion of the PAP. The contours in the area of the drainage feature in the south-central portion of the PAP illustrate lower elevations of approximately 475 to 485 feet NAVD88 (**Appendix A**). Prior to creation of Newton Lake, the elevation of the land surface east and southeast of the PAP was approximately 475 to 480 feet NAVD88.

2.2 Regional Geomorphology

The PAP, as well as all of Jasper County, is located within the Springfield Plain of the Till Plains Sections of the Central Lowlands Province. The Springfield Plain physiographic province is comprised largely of Illinoian glacial drift (Willman et al., 1975). The region is characterized by relatively flat to gently rolling topography. The uppermost geologic materials consist primarily of unconsolidated eolian, slopewash, and fluvial deposits underlain by superglacial and subglacial deposits associated with recent glaciations. The topography of these materials is a function of the underlying bedrock surface on which the material was deposited, and eolian and fluvial processes which have been in effect from their deposition to the present.

The Embarras River and its tributaries drain much of the county and eventually flow into the Wabash River. The southwestern portion of the county, including the NPP, lies within the Little Wabash River Basin. Therefore, all surface drainage from the property flows to the Little Wabash River, which then flows into the Wabash River.

The highest point in Jasper County is at Island Grove, at an elevation of 624 feet NAVD88. The lowest elevation, 440 feet NAVD88, is located at the point on the Crawford County line, which is intersected by the Embarras River. With a total relief of only 184 feet, the surface features of Jasper County are nominal and reflect the moderate amount of erosional modification to the post-glacial topographic surface.

2.3 Soils

Surficial soils at the PAP are shown on **Figure 2-2** and based on Jasper County soil survey data, available in the Soil Survey Geographic (SSURGO) by the United States Department of Agriculture’s Natural Resources Conservation Service provided by Environmental Systems Research Institute (ESRI) web hosted layer. Soils surrounding the PAP, not including the Urban Land (#533) within the limits of the NPP, are identified as: Orthents (clayey, sloping) along the western, southern, and eastern boundaries of the PAP; Hickory silt loam (18 to 35 percent slopes) and Ava silt loam (2 to 5 percent slopes) adjacent to Newton Lake; Bluford silt loam, Wynoose silt loam (0 to 2 percent slopes), Racoon silt loam (0 to 2 percent slopes) and Atlas silt loam (5 to 10 percent slopes, eroded) west and northwest of the PAP within agricultural land.

2.4 Regional Geology

2.4.1 Regional Unlithified Deposits

The unlithified geologic deposits in Jasper County, Illinois primarily consists of loess overlying glacial drift from the Illinoian and Pre-Illinoian glaciers. The unlithified deposits in the region are derived from recent river deposition (alluvium), glacial outwash, and glacial till deposits. The hydrogeologic investigation conducted by Rapps (1997) is the basis for much of the descriptions provided below. From the surficial deposits downward, there are eight primary unlithified geologic units in the region consisting of:

- **Cahokia Formation:** Holocene stage deposits in floodplains and channels of modern rivers and streams. Generally, consists of poorly sorted sand, silt, and clay with wood and shell fragments with local deposits of sandy gravel.
- **Peoria Silt:** Wisconsinan Age deposits that commonly occur in upland areas and along valley walls in Illinois. They generally grade from sandy silt in the bluffs of major source river valleys (like the Mississippi Valley) to clayey silt away from the bluffs, where it is commonly thinner and relatively weathered (Hansel and Johnson, 1996). They are typically massive and consist predominantly of windblown silt from the valley floor, with local lenses of well-sorted, fine- to medium-grained sand (Willman and Frye, 1970).
- **Sangamon Soil:** Silt and clay soils formed during the interglacial period between the Illinoian and Wisconsinan Stages as a result of weathering of the upper portion of the Illinoian drift.
- **Hagarstown Member of the Glasford Formation:** Gravel, sand, and gravelly diamicton occurring as ice-contact deposits that commonly occurs as ridged drift in a distinctive belt of linear to curved ridges and knolls. Outwash plains of poorly sorted to well-sorted sand and gravel may be present between the ridges in many places (Killey and Lineback, 1983).
- **Vandalia Till Member of the Glasford Formation:** Sandy/silty till with thin, discontinuous lenses of silt, sand, and gravel (Lineback, 1979; Willman and Frye, 1970).
- **Mulberry Grove Member of the Glasford Formation:** Typically consists of a thin, lenticular unit of gray sandy silt (Willman et al., 1975). It represents the interval between the retreat of the glacier that deposited the Smithboro Member and the advance of the glacier that deposited the Vandalia Till.
- **Smithboro Till Member of the Glasford Formation:** Gray, compact, silty clay diamicton that is less friable than the overlying Vandalia Till, and was deposited by ice sheets moving northwest to southeast across the region (Jacobs and Lineback, 1969).
- **Banner Formation:** Undifferentiated diamictons that rest directly on bedrock and consist mostly of glacial diamictons and intercalated sand and gravel outwash.

The surficial Quaternary geologic deposits in the vicinity of the Site that were mapped on a regional scale are shown on **Figure 2-3**.

2.4.2 Regional Bedrock Geology

The unlithified deposits are underlain by Pennsylvanian age bedrock belonging to the Mattoon Formation. The Mattoon Formation is the youngest formation in the Pennsylvanian System in Illinois. It is underlain by the Bond Formation. The Mattoon Formation has a maximum thickness of more than 600 feet in the central part of the Illinois Basin in Jasper County. It is characterized by a complex sequence of thin limestones, coals, black fissile shales, underclays, thick gray shales, and several well-developed sandstones. The lateral extent of many of the named units has not been determined due to widely scattered outcrops and scarce subsurface data. However, coals and limestone units are considered to be as persistent as those in the underlying Bond Formation (Rapps, 1997).

2.4.3 Structure

The major geologic structural features within Illinois are depicted on **Figure 2-4**. The PAP is situated within the Fairfield Basin, one of the major structural features of the encompassing Illinois Basin. The Fairfield Basin, characterized as a smooth floored inner central deep basin, is bound to the west and northwest by the DuQuoin-Louden Monoclinal Belt, to the north and northeast by the LaSalle Anticlinal Belt, and to the south by the Cottage Grove-Rough Creek-Shawneetown Fault Zone (Buschbach and Kolata, 1991). North of the Rouch Creek Fault System, the strata dip gently to the west at approximately 15 to 20 feet per mile (ft/mi), which parallels the general north-south, asymmetrical syncline structure of the Illinois Basin (Hatch and Affolter, 2002).

2.4.4 Seismic Setting

A review of the available data from the United States Geological Survey (USGS), Illinois State Geological Survey (ISGS), and other available regional structural information was completed by Haley & Aldrich, Inc. (2018) for the Location Restriction Demonstration to address the requirements of 40 C.F.R. § 257.62 (Fault Areas). The review found that the Wabash Valley Fault System is located approximately 40 miles southeast of the PAP (**Figure 2-4**). The Wabash Valley Fault system within Illinois extends laterally for approximately 60 miles in a general north-northeastward to south-southwestward trend. Haley & Aldrich, Inc. (2018) found that the timeframe of the most recent activity on the Wabash Fault System is not known. Based on available geologic data and information reviewed, there are no active faults or fault damage zones that have had displacement in the Quaternary period reported within 200 feet of the PAP.

As required by 35 I.A.C. § 845.330, existing and new CCR SIs and lateral expansions of existing SIs must not be located in seismic impact areas, unless owners or operators demonstrate that the SI is designed to resist the maximum horizontal acceleration (g) in lithified earth material. This requirement is identical to that in 40 C.F.R. § 257.63. The definition of a seismic impact zone is “areas having a 2 percent or greater probability that the maximum expected horizontal acceleration, expressed as a percentage of the earth's gravitation pull, will exceed 0.10 g in 50 years.” Although the PAP is located within a seismic impact zone, it satisfies the demonstration requirements of 35 I.A.C. § 845.330. The AECOM report titled “CCR Certification Report: Initial Structural Stability Assessment, Initial Safety Factor Assessment, and Initial Flow Design Control System Plan for the Primary Ash Pond at Newton Power Station”, dated October 2016, includes engineering analysis, calculations, and findings that support the requirements of 40 C.F.R. § 257.63 (Haley & Aldrich, Inc., 2018), and, by extension, 35 I.A.C. § 845.330.

2.4.5 Mining Activities

The areas immediately surrounding the facility have never been mined. Based on the directory of coal mines for Jasper County (ISGS, 2021), the nearest coal mines in the vicinity of the PAP are located approximately 6.7 miles to the northeast (**Appendix B**).

2.5 Site Geology

A field investigation was performed in 2021 to collect additional data for the discussion of vertical and horizontal lithology, stratigraphy, chemical properties, and physical properties of geologic layers to a minimum of 100 feet below ground surface (bgs) as specified in 35 I.A.C. § 845.620(b). Field investigation locations are shown on **Figure 2-5**. Boring logs, monitoring well and piezometer construction forms obtained from investigations at the PAP are provided in **Appendix C**.

The Cahokia Formation, described in the regional geology above, occurs in modern river valleys and floodplains. If present, these deposits are expected to occur south of the PAP in areas that are currently beneath the surface water of Newton Lake. The principal types of unlithified materials present above the bedrock in the vicinity of the PAP consist of the following in descending order:

- **CCR and Fill Material:** CCR and reworked surface materials within and adjacent to the various CCR Units.
- **Peoria Silt and Sangamon Soil** (wind-blown deposits and weathered till)**:** Clays and silts, including the Peoria Silt (Loess Unit) in upland areas, underlain by the Sangamon Soil which is comprised of weathered glacial drift.
- **Hagarstown Member:** where present, consists of relatively thin sandy deposits between the clays and silts of the Sangamon Soil and the Vandalia Till.
- **Vandalia Till:** Compacted clay and silt glacial till with varying amounts of sand and gravel (diamicton).
- **Mulberry Grove Member:** Sand, silty sand, and sandy silt/clay units found between the Vandalia Till and the Smithboro Till. These sandy deposits are the first laterally continuous sands observed beneath the PAP.
- **Smithboro Till and Banner Formation:** Thick, gray, compacted silty clay diamicton of the Smithboro Till and the greenish-gray silty clay of the Banner Formation.

Cross-sections showing the subsurface materials encountered at the PAP are included in **Figures 2-6 through 2-8**.

2.5.1 CCR and Fill

CCR is present within most of the PAP at thicknesses between 17 to 19.5 feet thick as observed in XPW01 through XPW04 (**Appendix C**). The lowest bottom-of-ash elevation observed is approximately 486 feet in the center of a former drainage feature oriented north-south through the center of the PAP, whereas ash is potentially highest in elevation at approximately 550 feet along the outer edges of the PAP (**Figure 2-9**)[1]. Note, drawing S-69 (**Appendix A**) indicates the former drainage feature was filled to elevation 508 feet NAVD88 during construction. The bottom of ash surface appears to mirror the former drainage feature. Comparison of the bottom of ash contours and topographic contours indicate CCR fill may be 40 feet or greater within the former drainage feature.

Geotechnical analysis results from six samples collected from ash at soil borings XPW01, XPW03 and XPW04 yielded Unified Soil Classification System (USCS) soil classifications of silty sand and

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[1] Base of ash surface is being further evaluated as the construction permit is being developed.

poorly graded sand with silt. Sample locations are shown on **Figure 2-5,** the geotechnical results from the most recent investigation are summarized in **Table 2-1**, and laboratory reports are included in **Appendix D**. Geotechnical results from XPW01, XPW03 and XPW04 indicated the following:

- Average moisture content of 21.3 percent, with a range of 12.6 to 31.1 percent.
- Average total porosity (calculated) of 50 percent, with a range of 38 to 56 percent.
- Average dry density of 84.3 pounds per cubic foot (pcf), with a range of 73.9 to 103.6 pcf.
- Average specific gravity of 2.69, with a range of 2.650 to 2.741.
- Average grain size composition of 14 percent gravel, 60 percent sand, and 26 percent fines (silt and clay). The fines content ranged from 11.8 to 61.3 percent, with a median value of 18.9 percent.
- Geometric mean vertical hydraulic conductivity of 3.11 x 10^{-4} centimeters per second (cm/s) and ranged from 1.58 x 10^{-5} to 1.34 x 10^{-3} cm/s.

Solid samples were collected from XPW01, XPW02, XPW03 and XPW04 by Ramboll in 2021 for chemical analysis. The results of solid samples collected from within the PAP are summarized in **Table 2-2**.

Leachate wells were installed in XPW01, XPW02, XPW03 and XPW04 by Ramboll in 2021, and porewater samples were collected. The results of porewater samples collected from within the PAP are summarized in **Table 2-3**.

2.5.2 Peoria Silt and Sangamon Soil

The Peoria Silt and Sangamon Soil is present within the PAP at thicknesses up to approximately 46 feet as measured in APW15 and ranged from 3 to 46 feet thick as observed in APW05 and APW10 (**Appendix C**). The bottom of this geologic unit is at the lowest elevation of 469.5 feet NAVD88 (APW15) along the southern portion of the PAP while highest in elevation of 543.4 feet NAVD88 in the northwest corner of the PAP (**Figures 2-6 and 2-7**). Generally, the elevation of the bottom of this unit decreases from north to south across the PAP.

Geotechnical analysis results from two samples collected from the Peoria Silt and Sangamon Soil at soil borings APW11 and APW15 yielded USCS soil classifications of lean clay. Sample locations are shown on **Figure 2-5,** the geotechnical results from the most recent investigation are summarized in **Table 2-1**, and laboratory reports are included in **Appendix D**. Geotechnical results from these samples indicated the following:

- Average moisture content of 18.2 percent, with a range of 17.8 to 18.5 percent.
- Average porosity (calculated) of 33 percent, with a range of 32 to 34 percent.
- Average dry density of 110.8 pcf, with a range of from 109.8 to 111.7 pcf.
- Average specific gravity of 2.67 with a range of 2.65 to 2.69.
- Grain size composition of 0.6 percent gravel, 43 percent sand, and 56.5 percent fines (silt and clay).

Soil samples collected from the Peoria Silt and Sangamon Soil (APW11, APW13 and APW15) were also analyzed for chemical parameters. The results of soil samples collected from the Peoria Silt and Sangamon Soil are summarized in **Table 2-4**.

2.5.3 Hagarstown Member

A discontinuous sandy unit, the Hagarstown Member of the Pearl Formation was encountered at elevations ranging from approximately 497 feet NAVD88 (APW08) to 533 feet NAVD88 (APW12). The unit was encountered at thicknesses up to approximately 6.9 feet at APW18, but generally the thickness is less than 2 feet, where present.

Geotechnical analysis results from three samples collected from the Hagarstown Member at soil borings APW12 and APW13 yielded a USCS soil classification of poorly graded sand with silt. Sample locations are shown on **Figure 2-5,** the geotechnical results from the most recent investigation are summarized in **Table 2-1**, and laboratory reports are included in **Appendix D**. Geotechnical results from these samples indicated the following:

- Average moisture content of 14.9 percent, with a range of 8.4 to 21.2 percent.
- Average porosity (calculated) of 36 percent, with a range of 30 to 47 percent.
- Average dry density of 106.1 pcf, with a range of 87.1 to 118.3 pcf.
- Average specific gravity of 2.70, with a range of 2.649 to 2.694.
- Grain size composition of 10.6 percent gravel, 68.4 percent sand, and 21.0 percent fines (silt and clay).

Soil samples collected from the Hagarstown Member (APW12, APW13 and APW15) were also analyzed for chemical parameters. The results of soil samples collected from the Hagarstown Member are summarized in **Table 2-4**.

2.5.4 Vandalia Till

Thick glacial deposits of the Vandalia Till, which are laterally continuous beneath the Site and NPP, were encountered at elevations ranging from 425 feet NAVD88 (APW15) to 530 feet NAVD88 (AWP05). The unit was encountered at thicknesses up to 59 feet at APW07, while the average thickness is 26 feet.

Geotechnical analysis results from five samples collected from the Vandalia Till at soil borings APW14, APW17, SB300/APW18, and SB301 yielded a USCS soil classification of lean clay and silty clay. Sample locations are shown on **Figure 2-5**, the geotechnical results from the most recent investigation are summarized in **Table 2-1**, and laboratory reports are included in **Appendix D**. Geotechnical results from these samples indicated the following:

- Average moisture content of 14 percent, with a range of 12.4 to 16.6 percent.
- Average porosity (calculated) of 31 percent, with a range of 27 to 36 percent.
- Average dry density of 117.1 pcf, with a range of 108.8 to 122.7 pcf.
- Average specific gravity of 2.70, with a range of 2.697 to 2.709.
- Grain size composition of 1.7 percent gravel, 29.1 percent sand, and 69.2 percent fines (silt and clay).

Soil samples collected from the Vandalia Till (APW11, APW12, APW15 and APW17) were also analyzed for chemical parameters. The results of soil samples collected from the Vandalia Till are summarized in **Table 2-4**.

2.5.5 Mulberry Grove Member

Thin to moderately thick (3 to 17 feet), the Mulberry Grove member was encountered at elevations ranging from approximately 417 feet NAVD88 (APW15) to 483 feet NAVD88 (APW10). The unit generally slopes from approximately 483 feet NAVD88 in the northeast portion of the site near APW10 to 462 feet NAVD88 in the southwest portion of the site near APW08. The unit was encountered at thicknesses up to 30 feet at APW17, while the average thickness is approximately 10 feet. At APW12 (**Figure 2-8**) sand and gravel was not encountered at a similar elevation during drilling.

Geotechnical analysis results from five samples collected from the Mulberry Grove Member at soil borings APW13, APW15, APW17, and SB300/APW18 yielded USCS soil classifications of silty sand, poorly graded sand with silt and well graded sand with silt. Sample locations are shown on **Figure 2-5,** the geotechnical results from the most recent investigation are summarized in **Table 2-1**, and laboratory reports are included in **Appendix D**. Geotechnical results from these samples indicated the following:

- Average moisture content of 10.8 percent, with a range of 6.1 to 14.5 percent.
- Average porosity (calculated) of 32 percent, with a range of 30 to 35 percent.
- Average dry density of 113.5 pcf, with a range of 109.6 to 116.8 pcf.
- Average specific gravity of 2.67, with a range of 2.660 to 2.686.
- Grain size composition of 10.4 percent gravel, 69 percent sand, and 20.6 percent fines (silt and clay).

Soil samples collected from the Mulberry Grove Member (APW11, APW13 and APW14) were also analyzed for chemical parameters. The results of soil samples collected from the Mulberry Grove Member are summarized in **Table 2-4**.

2.5.6 Smithboro Till and Banner Formation

Thick glacial till of the Smithboro Till Member and Banner Formation, which are laterally continuous beneath the Site and NPP, was encountered at elevations ranging from approximately 412 feet NAVD88 (APW15) to 475 feet NAVD88 (APW10). The unit was encountered at thicknesses up to 36 feet (APW14), while the average thickness is 32 feet (based upon the two borings that encountered bedrock APW13 and APW14).

Geotechnical analysis results from eight samples collected from the Smithboro Till and Banner Formation at soil borings APW11, APW12, APW14, APW15, SB300/APW18, and SB301 yielded USCS soil classifications of lean clay and silty clay. Sample locations are shown on **Figure 2-5,** the geotechnical results from the most recent investigation are summarized in **Table 2-1**, and laboratory reports are included in **Appendix D**. Geotechnical results from these samples indicated the following:

- Average moisture content of 15.5 percent, with a range of 11.1 to 19.1 percent.
- Average porosity (calculated) of 32 percent, with a range of 29 to 38 percent.

- Average dry density of 115.1 pcf, with a range of 104.6 to 121.3 pcf.
- Average specific gravity of 2.70, with a range of 2.686 to 2.723.
- Grain size composition of 0 percent gravel, 24.2 percent sand, and 75.8 percent fines (silt and clay).

Soil samples collected from the Smithboro Till and Banner Formation (APW11, APW12, APW13, APW14 and APW17) were also analyzed for chemical parameters. The results of soil samples collected from within the PAP are summarized in **Table 2-4**.

2.5.7 Bedrock

Bedrock underlying the PAP is the Pennsylvanian Age Mattoon Formation, which consists of a complex sequence of thin limestones, coals, black fissile shales, underclays, thick gray shales, and several well-developed sandstones. Bedrock was encountered in borings APW13 and APW14 (**Appendix C**). The elevation of the top of bedrock ranged from 445.5 feet NAVD88 (APW13) to 432.9 feet NAVD88 (APW14). The top of bedrock was described as shale in both borings advanced to bedrock.

No bedrock samples were collected for geotechnical testing or chemical analysis. Boring locations are shown on **Figure 2-5**.

3. REGIONAL AND LOCAL HYDROGEOLOGY

3.1 Regional Hydrogeology

Aquifers in the area of the PAP generally fall into two broad categories: (1) unlithified sediments that are glacial or alluvial in origin and contain mostly sand and gravel deposits interbedded with clay and silt; and (2) bedrock aquifers consisting of sandstone and fractured limestone, which vary widely in permeability. To the east of the NPP, water-yielding sandstone formations occur at depths of 100 to 300 feet bgs (Selkregg et al., 1957). Groundwater available from bedrock units is mostly mineralized and rarely used as a source for potable water (Rapps, 2009).

Glacial deposits generally provide enough water for rural and residential water supplies. Sand and gravel deposits within the Glasford Formation and the Pearl Formation have been developed locally for domestic water supplies. Locally occurring discontinuous sand and gravel deposits exist along the bottomlands of Big Muddy Creek, which can sustain domestic and farm groundwater supplies. The water bearing zones at the PAP are the sandy horizons that occur within Mulberry Grove Member of the Glasford Formation and the intermittent sands of the Hagarstown Member of the Pearl Formation.

3.2 Site Hydrogeology

In 2015, a monitoring program consisting of six monitoring wells (APW05, APW06, APW07, APW08, APW09, and APW10) was established to comply with requirements of 40 C.F.R. § 257. In 2021, nine additional monitoring wells (APW05S, and APW11 through APW18) were installed to collect information to meet the requirements of Part 845. Construction details for monitoring wells and piezometers is provided in **Table 3-1** and locations are depicted in **Figure 3-1**. Boring logs, monitoring well and piezometer construction forms are provided in **Appendix C**.

3.2.1 Hydrostratigraphic Units

Materials have been categorized into six hydrostratigraphic units at the PAP based on stratigraphic relationships, geologic composition, and common hydrogeologic properties. The units, listed from surface downward, are summarized as follows:

- **CCR**: CCR consisting of fly and bottom ash within the PAP. CCR may be present from the surface (approximately 545 to 555 feet NAVD88) to a minimum elevation of approximately 475 feet NAVD88. Water elevations measured in piezometers screened within the PAP indicate the phreatic surface ranges from approximately 535 to 547 feet NAVD88, which is higher than surrounding monitoring wells.
- **UD/PMP:** The UD is composed of the low permeability silts and clays of the Peoria Silt and Sangamon Soil and the sandier soils of the Hagarstown Member (*i.e.,* PMP).
  - **Hagarstown Member/PMP**: The Hagarstown Member consists of the discontinuous, sandier deposits of the UD where present and overlies the Vandalia Till.
- **UCU:** The UCU consists of a thick package of the low permeability clay and silt of the Vandalia Till. This unit is a laterally continuous layer between the base of the CCR unit and the top of the uppermost aquifer.
- **Uppermost Aquifer**: The uppermost aquifer is composed of the Mulberry Grove Member, which has been classified as poorly graded sand, silty sand, clayey sand, and gravel.

- **LCU**: The LCU is comprised of low permeability silt and clay of the Smithboro Till Member and the Banner Formation.
- **Bedrock Confining Unit**: Bedrock was classified as shale of the Mattoon Formation in locations it was encountered in soil borings during 2021 investigation activities (APW13 and APW14).

3.2.2 Uppermost Aquifer

The uppermost aquifer includes saturated portions of the Mulberry Grove Member in the vicinity of the PAP. Groundwater monitoring for the uppermost aquifer is focused on this zone because it is continuous, moderate permeability, and likely to indicate potential impacts from the PAP. The top of uppermost aquifer was evaluated with respect to the location restrictions in 2018 (Haley & Aldrich, Inc., 2018) and provided in **Figure 3-2**. The top of the uppermost aquifer is separated from overlying CCR material by the low permeability Vandalia Till which was encountered at thicknesses up to 59 feet and an average thickness of 26 feet (**Figures 2-6 to 2-8**). The base of the uppermost aquifer is the top of the LCU containing the low permeability Smithboro Till and the Banner Formation.

3.2.3 Potential Migration Pathways

The UD consists of low permeability clays and silts of the Peoria Silt, Sangamon Soil, and discontinuous sand lenses of the Hagarstown Member. Monitoring wells APW02, APW03, APW04, APW05S, and APW12 are screened within the sandier deposits of the UD and may be utilized for monitoring shallow PMPs adjacent to the PAP.

3.2.4 Water Table Elevation and Groundwater Flow Direction

The elevations of water within the PAP (as observed in XPW01 through XPW04 and XSG01) are greater than the surrounding areas. The phreatic surface within the PAP between February and August 2021 averaged 542 feet NAVD88, ranging from 546.69 feet NAVD88 in XPW02 (located along the northern portion of the PAP) to 535.40 feet NAVD88 in XSG01 (located along the southern portion of the PAP) (**Figures 3-3 and 3-4)**.

Groundwater flow in the uppermost aquifer is generally from north to south. However, uppermost aquifer wells also display flow converging towards a former surface drainage feature located west of the PAP (**Figure 3-3 and 3-4**) and an area where the uppermost aquifer is lowest in elevation. Groundwater elevations vary seasonally, generally less than one foot per year, while across the PAP they range from approximately 490 to 530 feet NAVD88, although flow directions are generally consistent (historic contour maps are included in **Appendix E**).

Groundwater elevations in PMP wells are above those in the uppermost aquifer and range from approximately 518 feet NAVD88 (APW05S) to 535 feet NAVD88 (APW05S). Groundwater elevations within the UCU, LCU, and bedrock confining unit were not contoured because no wells are screened within these units.

3.2.4.1 Vertical Hydraulic Gradients

Vertical hydraulic gradients were calculated using available groundwater elevation data from February to August 2021 at nested well locations within the UD (*i.e.,* PMP) and uppermost aquifer wells. Vertical hydraulic gradients are presented in **Table 3-2**. The results of the vertical hydraulic gradient calculations for these hydrostratigraphic units are summarized below:

- UD (*i.e.,* PMP) to uppermost aquifer:
  - Gradients calculated between APW05 (uppermost aquifer) and APW05S (PMP) were downward for all events.
  - Gradients calculated between APW10 (uppermost aquifer) and APW04 (PMP) were downward for all events.
  - Gradients calculated between APW09 (uppermost aquifer) and APW03 (PMP) were downward for all events.

These results are consistent with previous vertical gradient calculations (OBG, 2017).

3.2.4.2 Impact of Existing Ponds and Ash Saturation

Water levels collected from XPW01 through XPW04 indicate the phreatic surface is above water levels observed in the uppermost aquifer; however, the groundwater elevation contours of the uppermost aquifer (**Figures 3-3 and 3-4)** illustrate flow towards the south and converges at the former drainage feature along the western edge of the PAP. The absence of a radial component of flow outward indicates the PAP does not significantly impact groundwater flow direction. Furthermore, there is a thick layer of UCU Vandalia Till separating the base of ash and top of uppermost aquifer.

Saturated ash has been observed within the PAP leachate wells (XPW01 through XPW04) located along the northern portion of the unit. The maximum thickness of saturated ash as measured at XPW03 ranged from 11.5 feet in June 2021 to 12.6 feet in February 2021. The minimum thickness of saturated ash as measured at XPW01 ranged from 7.7 feet in July 2021 to 8.2 feet in June 2021. Greater thicknesses of saturated ash are likely in the central portion of the PAP where the former drainage feature was present prior to filling (**Figure 2-9**).

3.2.4.3 Impact of Newton Lake on Groundwater Flow

The surface water elevation at Newton Lake measured from February 15 to March 9, 2021 ranged from 504.42 to 504.84 feet NAVD88 at location SG02 near the outfall from the Secondary Pond. Groundwater flow in the uppermost aquifer generally flows southwest across the PAP with potentiometric surface elevations at downgradient wells around 491 feet NAVD88 (approximately 15 feet lower than the Newton Lake elevation). This separation in groundwater and Lake elevations (and observed downward vertical gradients) indicates groundwater within the uppermost aquifer does not flow into Newton Lake.

Groundwater elevations observed at APW10 are approximately 2-feet higher than surface water in Newton Lake (506 feet NAVD88 versus 504 feet NAVD88). The uppermost aquifer also approaches the former land surface, now beneath Newton Lake, in this area. As illustrated in cross-section B-B’ (**Figure 2-7**), the uppermost aquifer may intersect the base of Newton Lake and interact with groundwater upgradient of the PAP.

3.2.5 Hydraulic Conductivities

3.2.5.1 Field Hydraulic Conductivities

Field hydraulic conductivity tests were conducted by Ramboll during the 2021 investigation. The results are summarized in **Table 3-3**, provided in **Appendix F**, and discussed below:

- **CCR**: Results of field hydraulic tests in wells screened within the CCR (XPW01 through XPW04) ranged from 1.0 x 10^{-3} to 2.3 x 10^{-1} cm/s, with a geometric mean of 2.0 x 10^{-2} cm/s.
- **UD**: No field hydraulic conductivity tests were performed by Ramboll in 2021 in wells screened within the Sangamon Soil of the UD. Previous field hydraulic conductivity tests conducted by NRT in 2017 in wells screened within the Sangamon Soil of the UD (APW02, APW03, and APW04) ranged from 5.14 x 10^{-6} to 4.53 x 10^{-5} cm/s, with a geometric mean hydraulic conductivity of 1.5 x 10^{-5} cm/s (OBG, 2017).
- **PMP**: Results of field hydraulic tests in wells screened within the Hagarstown PMP (APW05S and APW12) ranged from 6.1 x 10^{-4} to 1.5 x 10^{-2} cm/s, with a geometric mean hydraulic conductivity of 3.1 x 10^{-3} cm/s.
- **UCU**: No field hydraulic conductivity tests were performed as there are no wells screened within the UCU.
- **Uppermost Aquifer**: Results of field hydraulic tests in wells screened within the uppermost aquifer (APW11, APW13, APW14, APW15, APW16, APW17, and APW18) ranged from 2.0 x 10^{-4} to 1.5 x 10^{-1} cm/s, with a geometric mean of 6.8 x 10^{-3} cm/s. Previous field hydraulic conductivity tests conducted by NRT in 2017 obtained similar results with a geometric mean hydraulic conductivity of 1.2 x 10^{-3} cm/s (OBG, 2017). The highest conductivities are measured in APW15, APW16, and APW17, which is consistent with groundwater flow toward these wells. In addition, the grain-size analyses of the uppermost aquifer materials from two samples collected at APW17 were amongst the highest observed at the Site, with sand and gravel contents of 91.1 and 93.3 percent.
- **LCU**: No field hydraulic conductivity tests were performed as there are no wells screened within the LCU.
- **Bedrock**: No field hydraulic conductivity tests were performed as there are no wells screened within the bedrock unit.

3.2.5.2 Laboratory Hydraulic Conductivities

Falling head permeability tests (ASTM D5084 Method F) were performed in the laboratory on samples collected during the 2021 investigations. Sample locations are shown in **Figure 2-5**. The geotechnical laboratory report is provided in **Appendix D**. The results are summarized in **Table 2-1** and discussed below.

- **CCR**: Eight samples were collected from CCR borings XPW01 through XPW04. However, the two samples collected from XPW02 (8 to 8.5 and 16.5 to 17 feet bgs) were not representative of the ash and are not included in summary of CCR characteristics. Laboratory falling head permeability test results for the six CCR samples indicated a geometric mean vertical hydraulic conductivity of 3.1 x 10^{-4} cm/s with a range of 1.6 x 10^{-5} to 1.3 x 10^{-3} cm/s.
- **UD**: One sample was collected from the Sangamon Soil at borings APW11 and APW15. Laboratory falling head permeability test results in the UD indicated a geometric mean vertical hydraulic conductivity of 5.9 x 10^{-8} cm/s and ranged from 3.1 x 10^{-8} to 8.6 x 10^{-8} cm/s. These values are lower than previous samples collected by NRT in 2017, with a geometric mean hydraulic conductivity of 1.3 x 10^{-5} cm/s (OBG, 2017).
- **PMP**: Three samples were collected from the Hagarstown Member, a PMP within the UD, at borings APW12 and APW13. Laboratory falling head permeability test results for the

Hagarstown Member indicated a geometric mean vertical hydraulic conductivity of 3.5×10^{-5} cm/s and ranged from 1.1×10^{-7} to 9.6×10^{-5} cm/s.

- **UCU**: Four samples were collected from the Vandalia Till at borings APW14, APW17, SB300/APW18, and SB301. Laboratory falling head permeability test results for the UCU samples indicated a geometric mean vertical hydraulic conductivity of 6.7×10^{-8} cm/s and ranged from 3.3×10^{-8} to 9.7×10^{-8} cm/s. These values are similar to a previous investigation completed by Rapps (1997) with hydraulic conductivity values ranging from 6.3×10^{-9} to 2.1×10^{-8} cm/s with a geometric mean hydraulic conductivity of 1.1×10^{-8} cm/s (Rapps, 1997).
- **UA**: Five samples were collected from the Mulberry Grove Formation at borings APW13, APW15, APW17, and APW18. Laboratory falling head permeability test results for the Mulberry Grove Formation indicated a geometric mean vertical hydraulic conductivity of 3.2×10^{-4} cm/s and ranged from 3.5×10^{-6} to 7.2×10^{-4} cm/s.
- **LCU**: Eight samples were collected from the glacial tills of the Smithboro Till at borings APW11, APW12, APW14, APW15, APW18, and SB301. Laboratory falling head permeability test results for the Smithboro Till indicated a geometric mean vertical hydraulic conductivity of 9.3×10^{-8} cm/s and ranged from 2.4×10^{-8} to 2.7×10^{-7} cm/s. No samples were collected from the Banner Formation of the LCU.
- **Bedrock**: No bedrock samples were analyzed.

3.2.6 Horizontal Groundwater Gradients and Flow Velocity

In the vicinity of the PAP, groundwater generally flows from north to south/southwest in the uppermost aquifer. Groundwater elevations and flow directions near the PAP are illustrated in 2021 contour maps (**Figures 3-3 and 3-4**). There is little seasonal variation in groundwater flow direction in the unlithified materials regardless of the lake elevation, as illustrated in **Figures 3-3 and 3-4** (historic contour maps are included in **Appendix E**). Horizontal gradients determined in 2021 across the PAP between wells APW10 and APW17 were very stable around the average of 2.5×10^{-3} feet/feet (ft/ft) with an average groundwater velocity of 1.88 feet per day (ft/day) (**Table 3-4**).

Horizontal gradients determined in 2021 across the northeastern portion of the CCR unit were very stable around the average of 7.1×10^{-3} ft/ft with an average groundwater velocity of 0.04 ft/day (**Table 3-4**).

3.2.7 Groundwater Classification

Per 35 I.A.C. § 620.210, groundwater within the uppermost aquifer at the PAP meets the definition of Class I – Potable Resource Groundwater based on the following criteria:

- Groundwater is located more than 10 feet bgs and within an unconsolidated silty sand and gravel unit which is five feet or more in thickness.
- Hydraulic conductivity exceeds the 1×10^{-4} cm/s criterion (**Table 3-3**).
- Groundwater is not downgradient of or underlying previously mined out areas.

Testing of the unconsolidated materials of the Mulberry Grove Member averaged 21 percent fines, which is greater than the 12 percent fines criterion (Section 2.5.5); however, this was not deemed prohibitive of the Class I Classification.

3.3 Surface Water Hydrology

3.3.1 Climate

Jasper County has a humid and temperate climate with a normal annual total precipitation of approximately 40 inches. Approximately two-thirds of the precipitation falls from April through September and is produced primarily by thunderstorms, with May having the highest average monthly precipitation. The average annual snowfall for the area is approximately 15 inches.

Average climatic data was obtained from the Illinois State Water Survey (ISWS). The data was recorded between 1989 and 2020 from Olney, Illinois, which is located approximately 16.5 miles southeast of the NPP. The data includes monthly maximum and minimum temperatures (degrees Fahrenheit [°F]) and monthly average rainfall calculated from daily values collected over the 31-year period. The data is summarized in **Table A.**

Table A. Average Monthly Temperature Extremes and Precipitation for Olney, IL

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Max Temperature (°F)	38.8	43.5	54.0	65.6	74.9	83.8	86.4	85.2	79.8	67.9	54.1	42.4	64.7
Min Temperature (°F)	23.2	26.4	35.0	44.7	54.8	63.4	66.6	64.3	56.4	45.2	35.2	26.9	45.2
Precipitation (inches)	3.10	2.39	3.37	4.23	4.64	3.82	4.04	2.73	2.97	3.66	3.81	3.25	42.0

https://www.isws.illinois.edu/warm/stationmeta.asp?site=OLN&from=wx

3.3.2 Surface Waters

The major surface water body in the vicinity of the PAP is Newton Lake, an elongated body of water that borders the PAP on three sides (south, east, and west). The southern boundary of the PAP runs parallel to the north shore of the lake and is located approximately 250 to 700 feet from the water's edge (**Figure 1-1**). The surface water elevation measured from February 15 to March 9, 2021 ranged from 504.42 to 504.84 feet NAVD88 at location SG02 near the outfall from the Secondary Pond. Surface water elevations in Newton Lake are not expected to fluctuate greatly as a result of the lake elevation being controlled by a dam to provide cooling water for the NPP.

The phreatic surface within the PAP as measured at XSG01 and XPW01 through XPW04 ranged from 535.4 to 546.69 feet NAVD88 between February and July in 2021. Other surface waters in the vicinity include small freshwater ponds.

Other primary drainage ways in the area are Big Muddy Creek and Wolf Creek, which lie approximately 2.3 miles west and 1.7 miles east of the Site, respectively. In addition, minor streams and drainage channels cut across the drift plain in the area.

4. GROUNDWATER QUALITY

4.1 Summary of Groundwater Monitoring Activities

4.1.1 IEPA Program Monitoring

In accordance with NPDES Permit No. IL0049191 (effective October 1, 2015), samples are collected quarterly from four monitoring wells (G116, APW02, APW03, and APW04) for laboratory and/or field parameters listed in Special Condition No. 19 of the NPDES Permit. Groundwater monitoring results from sampling of these four wells are reported to IEPA annually in accordance with the NPDES Permit. Of the four wells monitored as part of the NPDES Permit monitoring, two wells (APW03 and APW04) are located downgradient of the PAP. The results of NPDES Permit monitoring wells APW03 and APW04 are not included in the discussion in **Section 4.2** as the groundwater samples were not analyzed for total metals.

4.1.2 40 C.F.R. § 257 Program Monitoring and Well Network

The 40 C.F.R. § 257 monitoring well network consists of six groundwater monitoring wells screened in the uppermost aquifer, including two background monitoring wells (APW05 and APW06) and four compliance wells (APW07, APW08, APW09, and APW10). The boring logs, well construction forms, and other related monitoring well forms for the well network are included in **Appendix C** of this HCR. The well locations are shown on **Figure 3-1**.

Groundwater is being monitored at the PAP in accordance with the Detection Monitoring Program requirements specified in 40 C.F.R. § 257.95. Details of the procedures and techniques used to fulfill the groundwater sampling and analysis program requirements are found in the Sampling and Analysis Plan for the PAP (NRT, 2017). Results are discussed in Section 4.2.

Groundwater samples are collected semi-annually and analyzed for the field and laboratory parameters from Appendix III of 40 C.F.R. § 257, summarized in **Table B** below.

Table B. 40 C.F.R. § 257 Groundwater Monitoring Program Parameters

Field Parameters[1]		
Groundwater Elevation	pH	
Appendix III Parameters (Total, except TDS)		
Boron	Chloride	Sulfate
Calcium	Fluoride	TDS

[1] Dissolved oxygen, temperature, specific conductance, oxidation/reduction potential, and turbidity are recorded during sample collection.

4.1.3 Part 845 Well Installation and Monitoring

In 2021, nine additional monitoring wells (APW11, APW12, APW13, APW14, APW15, APW16, APW17, APW18, and APW5S) were installed along the perimeter of the PAP to assess the vertical and horizontal lithology, stratigraphy, chemical properties, and physical properties of geologic layers to a minimum of 100 feet bgs as specified in 35 I.A.C. § 845.620(b). Additionally, four leachate monitoring wells (XPW01, XPW02, XPW03, and XPW04) were installed within the PAP unit to characterize CCR materials and leachate. These locations and samples were discussed in **Section 2.5.1**. The boring logs, well construction forms, and other related monitoring well forms for the well network are included in **Appendix C** of this HCR. The well locations are shown on **Figure 3-1**.

Prospective monitoring wells (APW02, APW03, APW04, APW05, APW05S, APW06, APW11, APW12, APW13, APW14, APW15, APW16, APW17, and APW18) were sampled for eight rounds between February and August 2021 and the results were used to develop this HCR and assess well locations for inclusion in the PAP Part 845 monitoring well network.

Groundwater samples were analyzed for 35 I.A.C. § 845.600 parameters summarized in **Table C** below. Part 845 groundwater monitoring results are included below in **Section 4.2**. A summary of groundwater analytical results is presented in **Table 4-1**.

Table C. Part 845 Groundwater Monitoring Program Parameters

Field Parameters[1]			
pH	Turbidity	Groundwater Elevation	
Metals (Total)			
Antimony	Boron	Cobalt	Molybdenum
Arsenic	Cadmium	Lead	Selenium
Barium	Calcium	Lithium	Thallium
Beryllium	Chromium	Mercury	
Inorganics (Total)			
Fluoride	Sulfate	Chloride	TDS
Other (Total)			
Radium 226 and 228 combined			

[1] Dissolved oxygen, temperature, specific conductance, and oxidation/reduction potential were recorded during sample collection.

4.2 Groundwater Monitoring Results and Analysis

Groundwater data collected from the 40 C.F.R. § 257 network monitoring wells between 2015 and 2021 and from the wells installed in 2021 were evaluated with respect to standards included in 35 I.A.C. § 845.600(a)(1). This data set was selected because it includes parameters (total metals) consistent with the parameter list in 35 I.A.C. § 845.600(a)(1). The groundwater analytical results are summarized in **Table 4-1** and discussed in the subsections below. Groundwater elevations and field parameters are included in **Table 4-2**. Results indicate that the parameters discussed in the following sections were detected at concentrations greater than the applicable 35 I.A.C. § 845.600(a)(1) standards and are considered potential exceedances[1].

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[1] Potential exceedances include results reported during the eight rounds of baseline groundwater monitoring that are greater than the applicable 35 I.A.C. § 845.600(a)(1) standards. The results are considered potential exceedances because they were compared directly to the standard and did not include an evaluation of background groundwater quality or apply the statistical methodologies proposed in the Groundwater Monitoring Plan (GMP). For simplicity, "GWPS" will be used hereafter in discussing potential exceedances. Exceedances will be determined following IEPA approval of the GMP.

4.2.1 Arsenic

Arsenic was detected at concentrations greater than the GWPS (0.01 milligrams per liter [mg/L]) at six uppermost aquifer wells: downgradient wells APW08, APW09, APW15, and APW16; and background wells APW05 and APW06. Arsenic concentrations in downgradient wells ranged from 0.0039 to 0.022 mg/L. Arsenic concentrations in background wells ranged from 0.003 to 0.022 mg/L.

4.2.2 Chloride

Chloride was detected at concentrations greater than the GWPS (200 mg/L) in upgradient UD well APW05S and downgradient uppermost aquifer well APW15. Chloride concentrations in APW05S ranged from 180 to 550 mg/L. Chloride concentrations in uppermost aquifer well APW15 ranged from 230 to 260 mg/L.

4.2.3 Cobalt

Cobalt was detected at concentrations greater than the GWPS (0.006 mg/L) at PMP well APW12 with concentrations ranging from 0.0032 to 0.0073 mg/L. Concentrations have been below the GWPS for the last four consecutive sampling events.

4.2.4 Fluoride

Fluoride was detected at concentrations greater than the GWPS (4.0 mg/L) at downgradient uppermost aquifer well APW15 during one event (8.16 mg/L) and at APW18 with concentrations ranging from 0.597 to 7.02 mg/L.

4.2.5 Lead

Lead was detected at concentrations greater than the GWPS (0.0075 mg/L) at downgradient uppermost aquifer wells APW08, APW11, and APW18 with concentrations ranging from less than the reporting limit to 0.014 mg/L. Concentrations are less than the GWPS for the last five consecutive events.

4.2.6 Lithium

Lithium was detected at concentrations greater than the GWPS (0.04 mg/L) at three PMP wells APW02, APW04, and APW12; one upgradient UD well APW05S; and two downgradient uppermost aquifer wells APW13 and APW14. Lithium concentrations in the PMP wells ranged from 0.02 to 0.3 mg/L. Lithium concentrations in the upgradient well APW05S ranged from 0.038 to 0.091 mg/L. Lithium concentrations in the downgradient uppermost aquifer wells ranged from 0.024 to 0.054 mg/L.

4.2.7 pH

Groundwater samples collected with pH measurements below the lower range of the GWPS (6.5 standard units [SU]) were observed at four PMP wells APW02, APW03, APW04, APW12, one background well APW06, and two downgradient uppermost aquifer wells APW11 and APW13. Observed pH measurements in these PMP wells ranged from 5.4 to 7.7 SU. Observed pH measurements in the background well ranged from 6.4 to 7.8 SU. Observed pH measurements in these downgradient uppermost aquifer wells ranged from 6.1 to 7.4 SU.

4.2.8 Radium 226 and 228 Combined

Radium 226 and 228 combined was detected at concentrations greater than the GWPS (5 picocuries per liter [pCi/L]) at downgradient uppermost aquifer well APW16 with concentrations ranging from 0.946 to 5.85 pCi/L.

4.2.9 Sulfate

Sulfate can be a primary indicator parameter of CCR leachate impacts on groundwater quality. Sulfate was detected at concentrations greater than the GWPS (400 mg/L) at three PMP wells APW02, APW04, and APW12; upgradient UD well APW05S; and one downgradient uppermost aquifer well APW10. Concentrations of sulfate in these PMP wells ranged from 290 to 3,200 mg/L. Concentrations of sulfate in the upgradient well ranged from 200 to 2,100 mg/L. Concentrations of sulfate in the downgradient uppermost aquifer well (APW10) ranged from 390 to 540 mg/L.

4.2.10 Thallium

Thallium was detected at concentrations greater than the GWPS (0.002 mg/L) at one background well APW06, and two downgradient uppermost aquifer wells APW11 and APW18. Concentrations of thallium in the background well ranged from less than the reporting limit to 0.0025 mg/L. Concentrations of thallium in these downgradient uppermost aquifer wells ranged from less than the reporting limit to 0.0036 mg/L.

4.2.11 Total Dissolved Solids

TDS was detected at concentrations greater than the GWPS (1,200 mg/L) at four PMP wells APW02, APW03, APW04, and APW12; and one upgradient UD well APW05S. Concentrations of TDS at these PMP wells ranged from 540 to 5,300 mg/L. Concentrations at this upgradient well ranged from 3,200 to 3,800 mg/L.

5. EVALUATION OF POTENTIAL RECEPTORS

5.1 Water Well Survey

A potable water well inventory was completed in 2021 utilizing state databases to assess nearby pumping wells, drinking water receptors, and other uses of water in the vicinity of the PAP. The following sources of information were queried to identify well locations, drinking water receptors, and other uses of water within 1,000 meters of the PAP boundary:

- ISGS Illinois Water and Related Wells (ILWATER) Map[2]

A search of the ILWATER Map identified two wells located within 1,000-meters of the PAP (Well Nos. 120790038600 and 120790043600). Both wells are located to the southeast, or side-gradient, of the PAP and are listed as dry and abandoned. The assessment concluded there are no existing off-site water wells, potable or non-potable, that could potentially be impacted by groundwater from the PAP. The water well potential receptors are detailed in **Appendix B**.

5.2 Surface Water

A search was performed utilizing the United States Fish and Wildlife Service (USFWS) Wetlands Mapper[3] and the USGS National Map[4] for surface water bodies within 1,000 meters of the PAP. The predominant surface water body nearest the PAP is Newton Lake. Newton Lake is an approximately 1,648-acre freshwater lake partially encircling the PAP along the east, west, and south sides and at its closest point is approximately 240 feet downgradient from the PAP.

Additional surface water features indicated in the USFWS Wetlands Mapper and USGS National Map include several freshwater ponds ranging from 0.27 acres to 6.16 acres located generally north, west, and south of the PAP, riverine wetlands located north and northwest of the PAP, and an approximately 13.7-acre lake located to the north of the PAP.

The USGS National Map places the PAP within the Weather Creek Watershed (Hydrologic Unit Code [HUC] 051201140504), which is part of the Big Muddy Creek Watershed (HUC 0512011405) and located within the larger Little Wabash subbasin (HUC 05120114). The HUC watershed location is presented in **Appendix B**.

A Federal Emergency Management Agency (FEMA) Flood Insurance Rate Map for Jasper County (Map No. 1709900125B; Effective Date: January 17, 1985 is attached in **Appendix G** and can also be viewed online at: https://www.illinoisfloodmaps.org/dfirm.aspx?county=jasper. No base flood elevation has been established for this region.

5.3 Nature Preserves, Historic Sites, Endangered/Threatened Species

A search of the Illinois Department of Natural Resources (IDNR) Natural Heritage Database[5] for natural areas and protected areas within 1,000 meters of the PAP was performed. No natural or protected areas were identified within 1,000 meters of the PAP (**Appendix B**).

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[2] ISGS ILWATER Map: https://prairieresearch.maps.arcgis.com/apps/webappviewer/index.html?id=e06b64ae0c814ef3a4e43a191cb57f87
[3] USFWS Wetlands Mapper: https://www.fws.gov/wetlands/data/mapper.html
[4] USGS National Map: https://apps.nationalmap.gov/viewer/
[5] IDNR Natural Heritage Database: https://www2.illinois.gov/dnr/conservation/NaturalHeritage/Pages/NaturalHeritageDatabase.aspx

The IDNR Natural Heritage Database Threatened and Endangered Species by County[6] lists 25 threatened and endangered species as located within Jasper County, including 18 endangered and 7 threatened species. Habitats for endangered or threatened species are identified at the county level only (**Appendix B**).

Additionally, a search of the IDNR Historic Preservation Division[7] databases for historic sites in the vicinity of the PAP yielded no results within 1,000 meters of the PAP. The Illinois State Archaeological Survey (ISAS)[8] databases that do not require credentials to access were also searched and yielded no results within 1,000 meters of the PAP.

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[6] Illinois Threatened and Endangered Species by County: https://www2.illinois.gov/dnr/ESPB/Documents/ET_by_County.pdf
[7] IDNR Historic Preservation Division: https://www2.illinois.gov/dnrhistoric/Pages/default.aspx
[8] ISAS: https://www.isas.illinois.edu/

6. CONCLUSIONS

Hydrogeologic characterization of the PAP was originally developed as part of the *Hydrogeologic Investigation and Groundwater Monitoring Program, Newton Power Station, Jasper County, Illinois* (Rapps, 1997) and most recently updated for this HCR. Results of these hydrogeologic studies were reintroduced in this HCR and updated to include geologic, hydrogeologic, and groundwater quality data collected with a focus on the PAP (Part 845 regulated) CCR Unit and subject of this HCR.

The data were summarized and evaluated for changes in groundwater conditions since the previous investigations; available groundwater quality data for the PAP was compared to the to the Part 845 Standards.

The results of the hydrogeologic and groundwater quality evaluation are:

- There are six types of unlithified material present in the vicinity of the PAP, these include the following in descending order:
  - **CCR and Fill Material:** CCR and reworked surface materials within and adjacent to the various CCR Units.
  - **Peoria Silt and Sangamon Soil** (wind-blown deposits and weathered till)**:** Clays and silts, including the Peoria Silt (Loess Unit) in upland areas, underlain by the Sangamon Soil which is comprised of weathered glacial drift.
  - **Hagarstown Member:** Where present, consists of relatively thin sandy deposits between the clays and silts of the Sangamon Soil and the Vandalia Till.
  - **Vandalia Till Member:** Compacted clay and silt glacial till with varying amounts of sand and gravel (diamicton).
  - **Mulberry Grove Member:** Sand, silty sand, and sandy silt/clay units found between the Vandalia Till and the Smithboro Till. These sandy deposits are the first laterally continuous sands observed beneath the PAP.
  - **Smithboro Till Member and Banner Formation:** Thick, gray compacted silty clay diamicton of the Smithboro Till and the greenish-gray silty clay of the Banner Formation.
- Bedrock underlying the PAP is the Pennsylvanian Age Mattoon Formation, which consists of a complex sequence of thin limestones, coals, black fissile shales, underclays, thick gray shales, and several well-developed sandstones.
- Six hydrostratigraphic units have been identified at the PAP based on stratigraphic relationships and common hydrogeologic characteristics, these include the following in descending order:
  - **CCR**: CCR consisting of fly and bottom ash within the PAP.
  - **UD/PMP**: The UD is composed of the low permeability silts and clays of the Peoria Silt and Sangamon Soil and the sandier soils of the Hagarstown Member (*i.e.,* PMP).
    - **Hagarstown Member/PMP**: The Hagarstown Member consists of the discontinuous, sandier deposits of the UD where present and overlies the Vandalia Till.
  - **UCU**: This unit consists of the low permeability clay and silt of the Vandalia Till.

  - **Uppermost Aquifer**: This unit is composed of the Mulberry Grove Formation, which onsite has been classified as poorly graded sand, silty sand, clayey sand, and gravel.
  - **LCU**: This unit is comprised of low permeability silt and clay of the Smithboro Till and the Banner Formation.
  - **Bedrock Confining Unit**: Bedrock was classified as shale of the Mattoon Formation in locations it was encountered during 2021 investigation activities (APW13 and APW14).

- Groundwater within the uppermost aquifer flows generally from north to south. However, uppermost aquifer wells also display flow converging towards a former surface drainage feature located west of the PAP (resulting in a southwest flow direction). Groundwater elevations vary seasonally, generally less than one foot per year, while across the PAP they range from approximately 490 to 530 feet NAVD88, although flow directions are generally consistent.
- The surface water elevation at Newton Lake measured from February 15 to March 9, 2021 ranged from 504.42 to 504.84 feet NAVD88 at location SG02. Groundwater flow in the uppermost aquifer generally flows southwest across the PAP with potentiometric surface elevations at downgradient wells around 491 feet (approximately 15 feet lower than the lake elevation). This separation in groundwater and Lake elevations (and observed downward vertical gradients) indicates groundwater does not flow into Newton Lake.
- Groundwater velocities in the uppermost aquifer range from 0.04 ft/day in the north and east portion of the site to 1.9 ft/day in the south and west portion of the PAP.
- The phreatic surface within the PAP is higher than groundwater elevations; however, there is a significant thickness of low permeability Vandalia Till (UCU) that separates the base of the unit from the uppermost aquifer. Groundwater flow within the uppermost aquifer does not appear to be influenced by the PAP.
- Based on the detailed geologic information provided, and the hydrogeologic and groundwater quality data, groundwater within the uppermost aquifer at the PAP is classified as Class I – Potable Resource Groundwater.
- Arsenic, chloride, fluoride, lead, lithium, pH, radium 226 and 228 combined, sulfate, and thallium were detected at concentrations/measurements greater than the GWPS in downgradient uppermost aquifer wells. Cobalt, lithium, pH, sulfate, and TDS were detected at concentrations/measurements greater than the GWPS at PMP wells. Arsenic, chloride, lithium, pH, sulfate, thallium, and TDS were detected at concentrations/measurements greater than the GWPS in background monitoring wells.

This HCR satisfies Part 845 content requirements specific to 35 I.A.C. § 845.620(b) (Hydrogeologic Site Characterization) for the PAP at the NPP.

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TABLES

TABLE 2-1. GEOTECHNICAL DATA SUMMARY

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, ILLINOIS

Sample ID	Field Location ID	Top of Sample (ft bgs)	Bottom of Sample (ft bgs)	HSU	Moisture Content (%)	Dry Density (pcf)	Specific Gravity	Calculated Porosity [1] (%)	Vertical Hydraulic Conductivity (cm / s)	LL	PL	PI	Laboratory USCS	Gravel (%)	Sand (%)	Fines (%)
Sangamon Soil																
APW11	APW11	10	12	UD	17.8	111.7	2.645	32	8.57E-08	28	12	16	CL	1.1	45.1	53.8
APW15	APW15	20	22	UD	18.5	109.8	2.686	34	3.21E-08	33	10	23	CL	0.0	40.8	59.2
Hagarstown Member																
APW12	APW12	20	22	UD/PMP	15.1	118.3	2.694	30	1.07E-07	27	12	15	SC	7.4	46.8	45.8
APW12	APW12	25.5	26	UD/PMP	8.4	113.0	2.654	32	8.43E-06	10	13	NP	SP-SM	24.3	69.5	6.2
APW13	APW13	25	27	UD/PMP	21.2	87.1	2.649	47	9.63E-05	9	10	NP	SP-SM	0.0	88.9	11.1
Vandalia Till Member																
APW14	APW14	45	47	UCU	12.4	119.6	2.706	29	9.65E-08	26	14	12	CL	4.4	32.3	63.3
APW17	APW17	40	42	UCU	16.6	108.8	2.709	36	3.34E-08	26	13	13	CL	1.3	27.6	71.1
SB300	APW18	50	52	UCU	12.9	122.7	2.700	27	7.29E-08	32	12	20	CL	0.8	22.4	76.8
SB301	SB301	48	50	UCU	14.1	117.3	2.697	30	6.63E-08	27	14	13	CL	0.4	34.2	65.4
Mulberry Grove Member																
APW13	APW13	60.5	61	UA	14.5	114.3	2.661	31	2.18E-04	8	13	NP	SM	0.3	75.2	24.5
APW15	APW15	100.5	101	UA	12.1	116.4	2.665	30	3.50E-06	15	12	3	SM	4.4	49.8	45.8
APW17	APW17	71	71.5	UA	7.8	110.2	2.660	34	7.21E-04	5	9	NP	SW-SM	14.3	76.8	8.9
APW17	APW17	90.5	91	UA	6.1	116.8	2.672	30	6.39E-04	6	8	NP	SP-SM	28.2	65.1	6.7
SB300	APW18	61	61.5	UA	13.6	109.6	2.686	35	1.85E-05	5	9	NP	SM	4.7	78.2	17.1
Smithboro Till Member																
APW11	APW11	61	61.5	LCU	17.8	110.5	2.686	34	1.87E-07	27	18	9	CL	0.0	21.4	78.6
APW11	APW11	80	82	LCU	16.5	116.1	2.705	31	2.94E-08	32	14	18	CL	0.0	21	79
APW12	APW12	85	87	LCU	14.4	116.4	2.711	31	2.36E-08	29	14	15	CL	0.3	19.5	80.2
APW14	APW14	55.5	56	LCU	18.0	104.6	2.709	38	2.74E-07	25	15	10	CL	0.0	27.8	72.2
APW15	APW15	105	107	LCU	19.1	107.8	2.695	36	8.20E-08	29	13	16	CL	0.0	23.8	76.2
SB300	APW18	62.5	63	LCU	11.1	124.6	2.659	25	4.32E-06	20	14	6	CL-ML	0.0	42.4	57.6
SB300	APW18	105	107	LCU	14.1	116.4	2.710	31	4.28E-08	28	13	15	CL	0.0	30.7	69.3
SB301	SB301	68.5	69	LCU	13.1	121.3	2.723	29	4.05E-08	23	14	9	CL	0.0	31.3	68.7
SB301	SB301	98	100	LCU	15.7	118.2	2.720	30	6.13E-08	37	15	22	CL	0.0	17.8	82.2
CCR																
XPW01	XPW01	8.5	9	CCR	18.6	87.7	2.675	47	1.71E-04	47	57	NP	SP-SM	37.1	51.1	11.8
XPW01	XPW01	15.5	16	CCR	12.6	84.4	2.741	51	1.58E-05	35	17	18	CL	4.6	34.1	61.3
XPW03	XPW03	6	6.5	CCR	17.4	75.3	2.663	55	1.34E-03	33	27	6	SM	6.8	71.7	21.5
XPW03	XPW03	15.5	16	CCR	16.7	103.6	2.689	38	9.70E-05	12	19	NP	SM	16.4	67.3	16.3
XPW04	XPW04	6.5	7	CCR	31.1	73.9	2.697	56	1.61E-04	41	38	3	SM	1.6	84.5	13.9
XPW04	XPW04	15.5	16	CCR	31.1	80.8	2.650	51	7.83E-05	46	42	4	SM	15.7	51	33.3

TABLE 2-1. GEOTECHNICAL DATA SUMMARY

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, ILLINOIS

Sample ID	Field Location ID	Top of Sample (ft bgs)	Bottom of Sample (ft bgs)	HSU	Moisture Content (%)	Dry Density (pcf)	Specific Gravity	Calculated Porosity [1] (%)	Vertical Hydraulic Conductivity (cm/s)	LL	PL	PI	Laboratory USCS	Gravel (%)	Sand (%)	Fines (%)
Fill																
XPW02	XPW02	8	8.5	CCR	29.1	92.9	2.691	45	6.07E-08	36	16	20	CL	0.3	44.8	54.9
XPW02	XPW02	16.5	17	CCR	21.8	103.7	2.694	38	7.38E-08	36	14	22	CL	0.0	19.8	80.2

[O: SSW 04/22/21, U:EDP 08/23/21, U: SSW 08/26/21, C: LDC 08/31/21; U: LDC 09/16/21, C: SSW 09/21/21]

Notes:

[1] Porosity calculated as relationship of bulk density to particle density (n = 100[1- (pb/pd)])

% = Percent
bgs = below ground surface
CCR = coal combustion residuals
cm/s = centimeters per second
ft = foot/feet
in = inch
LL = Liquid limit
NP = Non Plastic
pcf = pounds per cubic foot
PI = Plastic Index
PL = Plasticity Limit

HSU = Hydrostratigraphic Unit
LCU = lower confining unit
PMP = potential migration pathway
UA = uppermost aquifer
UCU = upper confining unit
UD = upper drift

USCS = Unified Soil Classification System
CL - Lean Clay
CL-ML = Silty Lean Clay
SC = Clayey Sand
SM = Silty Sand
SP-SM = Poorly Graded Sand with Silt
SW-SM = Well Graded Sand with Silt

TABLE 2-2. ASH ANALYTICAL RESULTS

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, ILLINOIS

Sample Location	Sample Depth (ft BGS)	Sample Date	Antimony (mg/kg)	Arsenic (mg/kg)	Barium (mg/kg)	Beryllium (mg/kg)	Boron (mg/kg)	Cadmium (mg/kg)	Chromium (mg/kg)	Cobalt (mg/kg)	Lead (mg/kg)	Lithium (mg/kg)	Mercury (mg/kg)	Molybdenum (mg/kg)	Selenium (mg/kg)	Thallium (mg/kg)
XPW01	6-8	01/20/2021	<4.1	7.5	1800	1.6	260	<1.4	27	12	21	15	0.53	3.3	5.8	<1.4
XPW01	13-15	01/20/2021	<4	12	2400	2	390	<1.3	33	18	24	21	0.74	4.5	8.1	<1.3
XPW02	9-10	01/19/2021	<3	2.6	1900	1.2	94	<1	13	6.7	5	10	<0.2	1.2	<1	<1
XPW02	11.5-13.5	01/19/2021	<4.6	19	570	<1.5	69	<1.5	14	5	6.9	<7.7	<0.31	21	2.1	<1.5
XPW03	7.5-9	01/19/2021	<4.4	7.4	3600	1.8	280	<1.5	31	15	21	16	<0.29	3.6	3	<1.5
XPW03	17-19	01/19/2021	<3.6	27	490	1.3	95	<1.2	22	3.1	6.3	6.7	<0.24	3.4	1.3	<1.2
XPW04	13-15	01/19/2021	<3.4	9.4	1100	1.9	310	<1.1	26	13	21	18	0.69	3.6	5.9	<1.1
XPW04	17-19	01/19/2021	<5.6	9	4100	2.2	320	<1.9	33	15	21	18	<0.37	3.7	3.4	<1.9

Notes:

< = concentration is less than the concentration shown, which corresponds to the reporting limit for the method.
BGS = below ground surface
ft = feet
mg/kg = milligrams per kilogram

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TABLE 2-3. POREWATER ANALYTICAL RESULTS

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, ILLINOIS

Sample Location	Sample Date	Antimony, total (mg/L)	Arsenic, total (mg/L)	Barium, total (mg/L)	Beryllium, total (mg/L)	Boron, total (mg/L)	Cadmium, total (mg/L)	Calcium, total (mg/L)	Chloride, total (mg/L)	Chromium, total (mg/L)	Cobalt, total (mg/L)	Fluoride, total (mg/L)	Lead, total (mg/L)	Lithium, total (mg/L)	Mercury, total (mg/L)	Molybdenum, total (mg/L)	pH (field) (SU)	Radium 226 and 228 combined (pCi/L)	Selenium, total (mg/L)	Sulfate, total (mg/L)	Thallium, total (mg/L)
XPW01	02/17/2021	<0.003	0.042	0.035	<0.001	9.5	<0.004	62	49	<0.004	<0.008	2.17	<0.001	0.11	0.015	0.66	12.3	0.0059	0.23	19000	<0.001
XPW01	03/09/2021	<0.003	0.049	0.14	<0.001	11	<0.001	63	38	<0.004	<0.002	2.37	<0.001	0.13	0.014	0.59	12.4	0.211	0.21	14000	<0.001
XPW01	03/30/2021	<0.003	0.049	0.064	<0.001	9.9	<0.001	54	32	<0.004	<0.002	2.7	<0.001	0.14	0.011	0.54	12.4	0	0.19	19000	<0.001
XPW01	04/28/2021	<0.003	0.054	0.46	<0.001	10	<0.001	61	33	0.008	0.003	2.61	0.0039	0.074	0.013	0.53	12.3	0.157	0.17	12000	<0.001
XPW01	06/30/2021	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	1.19	--	--	--
XPW01	07/14/2021	<0.003	0.052	0.039	<0.001	12	<0.001	31	27	<0.004	<0.002	1.92	<0.001	0.15	0.012	0.38	12.2	0.167	0.12	11000	<0.001
XPW02	02/17/2021	<0.003	0.092	0.017	<0.001	2.3	<0.001	15	10	<0.004	<0.002	0.762	<0.001	<0.02	<0.0002	0.093	8.6	0.096	<0.001	160	<0.001
XPW02	03/09/2021	<0.003	0.091	0.024	<0.001	2.5	<0.001	20	9.6	<0.004	<0.002	0.61	<0.001	<0.02	<0.0002	0.097	9.2	0.705	<0.001	150	<0.001
XPW02	03/30/2021	<0.003	0.085	0.05	<0.001	2.4	<0.001	22	9.9	<0.004	<0.002	0.575	<0.001	0.026	<0.0002	0.1	8.9	0.832	<0.001	160	<0.001
XPW02	04/28/2021	<0.003	0.082	0.042	<0.001	2.6	<0.001	25	9.7	<0.004	<0.002	0.637	<0.001	0.023	<0.0002	0.11	9.9	0.668	<0.001	190	<0.001
XPW02	06/30/2021	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0.026	--	--	--
XPW02	07/14/2021	<0.003	0.077	0.025	<0.001	2.5	<0.001	21	10	<0.004	<0.002	0.508	<0.001	0.028	<0.0002	0.086	9.7	0.388	<0.001	160	<0.001
XPW03	02/17/2021	<0.003	0.036	0.069	<0.001	1.3	<0.001	42	14	<0.004	<0.002	0.466	<0.001	0.032	<0.0002	0.061	10.9	0.204	0.0023	92	<0.001
XPW03	03/09/2021	<0.003	0.031	0.11	<0.001	1.2	<0.001	47	9.2	<0.004	<0.002	0.569	<0.001	0.024	<0.0002	0.054	10.8	0.576	0.0038	93	<0.001
XPW03	03/30/2021	<0.003	0.014	0.088	<0.001	0.84	<0.001	44	13	<0.004	<0.002	0.384	<0.001	0.025	<0.0002	0.027	10.2	0.451	0.0019	94	<0.001
XPW03	04/28/2021	<0.003	0.035	0.37	<0.001	1.2	<0.001	55	11	0.0055	<0.002	0.598	0.0027	0.029	<0.0002	0.054	11.3	0.613	0.0017	96	<0.001
XPW03	06/30/2021	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	1.47	--	--	--
XPW03	07/14/2021	<0.003	0.032	0.44	<0.001	1.3	<0.001	72	11	0.0068	0.0021	0.372	0.0036	0.04	<0.0002	0.055	11.2	0.57	0.0019	120	<0.001
XPW04	02/17/2021	<0.003	0.0065	0.13	<0.001	2.5	<0.001	80	62	<0.004	<0.002	0.618	<0.001	0.021	0.00029	0.37	10.8	0.0723	0.055	2200	<0.001
XPW04	03/09/2021	<0.003	0.0067	0.15	<0.001	2.4	<0.001	65	34	<0.004	<0.002	0.602	<0.001	<0.02	<0.0002	0.19	10.0	0.374	0.028	1400	<0.001
XPW04	03/29/2021	<0.003	0.0062	0.3	<0.001	2.1	<0.001	53	31	0.005	<0.002	0.605	<0.001	<0.02	<0.0002	0.059	9.1	0.62	0.0074	600	<0.001
XPW04	04/28/2021	<0.003	0.0071	0.22	<0.001	2.8	<0.001	120	37	<0.004	<0.002	0.628	<0.001	0.02	0.00027	0.52	11.5	0.0889	0.083	3800	<0.001
XPW04	06/30/2021	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	1.66	--	--	--
XPW04	07/14/2021	<0.003	0.0067	0.089	<0.001	2.3	<0.001	60	34	<0.004	<0.002	0.542	<0.001	<0.02	<0.0002	0.14	10.0	0.36	0.02	1600	<0.001

TABLE 2-3. POREWATER ANALYTICAL RESULTS

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, ILLINOIS

Sample Location	Sample Date	Antimony, total (mg/L)	Arsenic, total (mg/L)	Barium, total (mg/L)	Beryllium, total (mg/L)	Boron, total (mg/L)	Cadmium, total (mg/L)	Calcium, total (mg/L)	Chloride, total (mg/L)	Chromium, total (mg/L)	Cobalt, total (mg/L)	Fluoride, total (mg/L)	Lead, total (mg/L)	Lithium, total (mg/L)	Mercury, total (mg/L)	Molybdenum, total (mg/L)	pH (field) (SU)	Radium 226 and 228 combined (pCi/L)	Selenium, total (mg/L)	Sulfate, total (mg/L)	Thallium, total (mg/L)

Notes:

Field readings are reported with as many significant figures as provided by analytical laboratory.
-- = data not available
< = concentration is less than the concentration shown, which corresponds to the reporting limit for the method.
mg/L = milligrams per liter
pCi/L = picocuries per liter
SU = standard units

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TABLE 2-4. SOIL ANALYTICAL RESULTS
HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, ILLINOIS

Sample Location	Geologic Unit	Sample Depth (ft BGS)	Sample Date	Antimony (mg/kg)	Arsenic (mg/kg)	Barium (mg/kg)	Beryllium (mg/kg)	Boron (mg/kg)	Cadmium (mg/kg)	Chromium (mg/kg)	Cobalt (mg/kg)	Lead (mg/kg)	Lithium (mg/kg)	Mercury (mg/kg)	Molybdenum (mg/kg)	Selenium (mg/kg)	Thallium (mg/kg)
APW11	Peoria Silt/Sangamon Soil	8-10	01/23/2021	<3.6	4.3	45	<1.2	<12	<1.2	7.3	9.4	8.5	<6.1	<0.24	<1.2	<1.2	<1.2
APW11	Mulberry Grove Member	62-64	01/23/2021	<3.5	2.8	16	<1.2	<12	<1.2	7.1	4.3	5.7	7.3	<0.23	<1.2	<1.2	<1.2
APW11	Smithboro Till Member	94-96	01/23/2021	<3.6	8.9	86	<1.2	<12	<1.2	9.8	5.7	8.6	<6	<0.24	1.2	<1.2	<1.2
APW12	Hagarstown Member	22-23.5	01/21/2021	<3.6	2.4	46	<1.2	<12	<1.2	13	7.4	8.4	10	<0.24	<1.2	<1.2	<1.2
APW12	Hagarstown Member	23.5-25	01/21/2021	<3.8	1.4	9.7	<1.3	<13	<1.3	<5.1	<2.5	1.7	<6.3	<0.25	<1.3	<1.3	<1.3
APW12	Smithboro Till Member	83-85	01/21/2021	<3.2	22	65	<1.1	<11	<1.1	11	9.4	13	7.8	<0.21	1.3	<1.1	<1.1
APW13	Sangamon Soil	23-25	01/22/2021	<3.1	2.4	41	<1	<10	<1	11	5.5	8.6	10	<0.21	<1	<1	<1
APW13	Mulberry Grove Member	58-60	01/22/2021	<4	4.6	25	<1.3	<13	<1.3	10	6.7	8.6	<6.6	<0.26	2.3	<1.3	<1.3
APW13	Banner Formation	78-80	01/22/2021	<3.1	5.9	57	<1	<10	<1	16	9.7	12	20	<0.21	2.5	<1	<1
APW14	Mulberry Grove Member	48-50	01/23/2021	<3.2	3.7	11	<1.1	<11	<1.1	6.6	3.9	6	6.3	<0.21	1.4	<1.1	<1.1
APW14	Smithboro Till Member	88-90	01/23/2021	<3.2	4.1	83	<1.1	<11	<1.1	12	7.2	15	9.6	<0.21	<1.1	1.2	<1.1
APW15	Hagarstown Member	23-25	01/21/2021	<3	<1	42	<1	<10	<1	5.1	<2	7.5	<5.1	<0.2	<1	<1	<1
APW15	Vandalia Till Member	85-87	01/21/2021	<3	1.8	14	<1	<10	<1	<4	<2	3.2	<5	<0.2	<1	<1	<1
APW15	Smithboro Till Member	102-104	01/22/2021	<3.5	1.8	14	<1.2	<12	<1.2	<4.7	<2.3	3.5	<5.9	<0.23	<1.2	<1.2	<1.2
APW17	Vandalia Till Member	38-40	01/22/2021	<3.1	3.4	21	<1	<10	<1	7.5	5.7	7.7	7	<0.21	1.5	<1	<1
APW17	Mulberry Grove Member	68-70	01/22/2021	<3	1.8	12	<1	<10	<1	<4	<2	2.8	<5	<0.2	<1	<1	<1
APW17	Mulberry Grove Member	88-90	01/22/2021	<3	5.9	37	<1	<10	<1	7.8	10	6.9	<5	<0.2	1.4	<1	<1

TABLE 2-4. SOIL ANALYTICAL RESULTS

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, ILLINOIS

Sample Location	Geologic Unit	Sample Depth (ft BGS)	Sample Date	Antimony (mg/kg)	Arsenic (mg/kg)	Barium (mg/kg)	Beryllium (mg/kg)	Boron (mg/kg)	Cadmium (mg/kg)	Chromium (mg/kg)	Cobalt (mg/kg)	Lead (mg/kg)	Lithium (mg/kg)	Mercury (mg/kg)	Molybdenum (mg/kg)	Selenium (mg/kg)	Thallium (mg/kg)
APW17	Smithboro Till Member	94-96	01/22/2021	<3.5	4.2	75	<1.2	<12	<1.2	8.6	4.6	7.4	7.6	<0.24	<1.2	<1.2	<1.2
XPW02	Fill	9-10	01/19/2021	<3	2.6	1900	1.2	94	<1	13	6.7	5	10	<0.2	1.2	<1	<1
XPW02	Fill	11.5-13.5	01/19/2021	<4.6	19	570	<1.5	69	<1.5	14	5	6.9	<7.7	<0.31	21	2.1	<1.5

Notes:

< = concentration is less than the concentration shown, which corresponds to the reporting limit for the method.
BGS = below ground surface
ft = foot or feet
mg/kg = milligrams per kilogram

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TABLE 3-1. MONITORING WELL LOCATIONS AND CONSTRUCTION DETAILS
HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, ILLINOIS

Well Number	HSU	Date Constructed	Top of PVC Elevation (ft)	Measuring Point Elevation (ft)	Measuring Point Description	Ground Elevation (ft)	Screen Top Depth (ft BGS)	Screen Bottom Depth (ft BGS)	Screen Top Elevation (ft)	Screen Bottom Elevation (ft)	Well Depth (ft BGS)	Bottom of Boring Elevation (ft)	Screen Length (ft)	Screen Diameter (inches)	Latitude (Decimal Degrees)	Longitude (Decimal Degrees)
APW02	UD	06/19/2010	533.61	533.61	Top of Riser	529.90	9.70	19.70	520.20	510.20	20.00	509.90	10	2	38.925918	-88.293907
APW03	UD	06/18/2010	532.41	532.41	Top of Riser	528.37	9.70	19.70	518.67	508.67	20.00	508.40	10	2	38.922322	-88.281567
APW04	UD	06/19/2010	525.06	525.06	Top of Riser	521.45	7.70	17.70	513.75	503.75	18.00	503.50	10	2	38.927444	-88.273113
APW05	UA	10/22/2015	544.07	544.07	Top of Riser	541.08	62.64	67.44	478.44	473.64	67.84	473.10	4.8	2	38.933958	-88.280983
APW05S	UD	01/19/2021	543.94	543.94	Top of PVC	541.05	10.00	20.00	531.05	521.05	20.00	518.10	10	2	38.933958	-88.281033
APW06	UA	10/21/2015	546.07	546.07	Top of Riser	542.89	67.67	72.48	475.22	470.41	72.88	468.90	4.8	2	38.933746	-88.286276
APW07	UA	11/05/2015	538.37	538.37	Top of Riser	535.72	77.89	82.70	457.83	453.02	83.10	452.60	4.8	2	38.928233	-88.292076
APW08	UA	10/28/2015	528.97	528.97	Top of Riser	526.26	71.40	81.06	454.86	445.20	81.53	444.30	9.7	2	38.923154	-88.292286
APW09	UA	11/03/2015	531.52	531.52	Top of Riser	528.33	56.66	61.46	471.67	466.87	61.85	466.30	4.8	2	38.922319	-88.281585
APW10	UA	11/06/2015	524.25	524.25	Top of Riser	521.49	40.74	45.54	480.75	475.95	45.94	475.60	4.8	2	38.927435	-88.273127
APW11	UA	01/23/2021	538.63	538.63	Top of PVC	536.05	60.00	65.00	476.05	471.05	65.00	436.10	5	2	38.932811	-88.27545
APW12	UD	02/21/2021	546.29	546.29	Top of PVC	543.33	20.00	30.00	523.33	513.33	30.00	456.30	10	2	38.92975	-88.272058
APW13	UA	01/22/2021	537.99	537.99	Top of PVC	535.16	58.50	63.50	476.66	471.66	63.50	445.20	5	2	38.92566	-88.274416
APW14	UA	01/23/2021	526.29	526.29	Top of PVC	523.85	50.00	55.00	473.85	468.85	55.00	428.90	5	2	38.924057	-88.277994
APW15	UA	01/22/2021	524.69	524.69	Top of PVC	522.06	98.00	103.00	424.06	419.06	103.00	412.10	5	2	38.921593	-88.285226
APW16	UA	01/20/2021	531.18	531.18	Top of PVC	529.16	80.50	85.50	448.66	443.66	85.50	419.20	5	2	38.920317	-88.291291
APW17	UA	01/22/2021	532.52	532.52	Top of PVC	529.84	87.00	92.00	442.84	437.84	92.00	429.80	5	2	38.925916	-88.293928
APW18	UA	01/21/2021	543.27	543.27	Top of PVC	540.55	75.00	80.00	465.55	460.55	80.00	433.60	5	2	38.930979	-88.290122
G48MG	UA	10/20/2015	545.53	545.53	Top of Riser	542.68	71.80	76.65	470.88	466.03	77.06	465.60	4.9	2	38.939248	-88.296012
G202	UA	10/16/1996	539.69	539.69	Top of Riser	536.85	64.00	74.00	472.85	462.85	74.00	462.90	10	2	38.930876	-88.290559
G203	UA	11/15/1996	533.13	533.13	Top of Riser	530.73	62.50	72.50	468.23	458.23	72.50	458.20	10	2	38.928597	-88.292217
G208	UA	10/13/2011	535.03	535.03	Top of Riser	533.19	74.93	94.71	458.26	438.48	94.80	438.20	19.8	2	38.929632	-88.298182
G217S	UD	08/26/1997	537.98	537.98	Top of Riser	535.54	9.00	19.00	526.54	516.54	19.00	510.50	10	2	38.932171	-88.290041

TABLE 3-1. MONITORING WELL LOCATIONS AND CONSTRUCTION DETAILS
HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, ILLINOIS

Well Number	HSU	Date Constructed	Top of PVC Elevation (ft)	Measuring Point Elevation (ft)	Measuring Point Description	Ground Elevation (ft)	Screen Top Depth (ft BGS)	Screen Bottom Depth (ft BGS)	Screen Top Elevation (ft)	Screen Bottom Elevation (ft)	Well Depth (ft BGS)	Bottom of Boring Elevation (ft)	Screen Length (ft)	Screen Diameter (inches)	Latitude (Decimal Degrees)	Longitude (Decimal Degrees)
G217D	UA	12/09/2014	537.92	537.92	Top of Riser	535.51	--	--	--	--	69.30	--	--	--	38.932174	-88.29008
G222	UA	10/25/2011	534.32	534.32	Top of Riser	532.38	64.57	79.24	467.81	453.14	79.30	452.40	14.7	2	38.927194	-88.299669
G223	UA	10/11/2011	533.60	533.60	Top of Riser	531.68	79.09	88.75	452.59	442.93	89.10	442.60	9.7	2	38.93016	-88.293451
G224	UA	10/05/2011	534.31	534.31	Top of Riser	532.31	63.51	73.17	468.80	459.14	73.50	458.30	9.7	2	38.931767	-88.292396
R202	UA	--	--	--	--	--	--	--	--	--	--	--	--	--	38.930879	-88.290581
R217D	UA	09/26/2017	538.18	538.18	Top of Riser	535.60	60.10	65.03	475.50	470.57	65.24	470.40	4.9	2	38.932191	-88.290118
XPW01	CCR	01/20/2021	551.76	551.76	Top of PVC	548.62	7.00	17.00	541.62	531.62	17.00	528.60	10	2	38.932212	-88.285525
XPW02	CCR	01/19/2021	554.43	554.43	Top of PVC	551.97	6.00	16.00	545.97	535.97	16.00	532.00	10	2	38.932343	-88.28289
XPW03	CCR	01/19/2021	553.65	553.65	Top of PVC	550.81	10.00	20.00	540.81	530.81	20.00	530.80	10	2	38.931062	-88.27641
XPW04	CCR	01/19/2021	554.51	554.51	Top of PVC	551.90	10.00	20.00	541.90	531.90	20.00	531.90	10	2	38.929888	-88.274073
XSG01	CCR	--	--	536.17	Staff gauge	--	--	--	--	--	--	--	--	--	38.923218	-88.29067
SG02	SW	--	--	506.89	Staff gauge	--	--	--	--	--	--	--	--	--	38.921234	-88.292057

Notes:
All elevation data are presented relative to the North American Vertical Datum 1988 (NAVD88), GEOID 12A
-- = data not available
BGS = below ground surface
CCR = Coal Combustion Residual
ft = foot or feet
HSU = Hydrostratigraphic Unit
PVC = polyvinyl chloride
SW = surface water
UA = uppermost aquifer
UD = upper drift

generated 10/05/2021, 4:23:16 PM CDT

TABLE 3-2. VERTICAL HYDRAULIC GRADIENTS

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER STATION
PRIMARY ASH POND
NEWTON, IL

Date	APW05S Groundwater Elevation (ft NAVD88)	APW05 Groundwater Elevation (ft NAVD88)	Head Change (ft)	Distance Change [1] (ft)	Vertical Hydraulic Gradient [2] (dh/dl)	
	PMP	UA				
2/15/2021	533.90	529.83	4.07	50.01	0.081	down
3/9/2021	533.71	529.61	4.10	50.01	0.082	down
3/29/2021	533.91	529.68	4.23	50.01	0.085	down
4/27/2021	533.56	529.73	3.83	50.01	0.077	down
5/25/2021	533.23	529.51	3.72	50.01	0.074	down
6/15/2021	532.54	529.42	3.12	50.01	0.062	down
6/24/2021	531.93	529.38	2.55	50.01	0.051	down
7/14/2021	532.16	529.33	2.83	50.01	0.057	down
			Middle of screen elevation APW05S			526.05
			Middle of screen elevation APW05			476.04

Date	APW04 Groundwater Elevation (ft NAVD88)	APW10 Groundwater Elevation (ft NAVD88)	Head Change (ft)	Distance Change [1] (ft)	Vertical Hydraulic Gradient [2] (dh/dl)	
	PMP	UA				
2/15/2021	518.19	506.65	11.54	30.40	0.38	down
3/9/2021	519.50	505.10	14.40	30.40	0.47	down
3/29/2021	520.34	506.94	13.40	30.40	0.44	down
4/27/2021	519.87	506.53	13.34	30.40	0.44	down
5/24/2021	519.73	506.35	13.38	30.40	0.44	down
6/15/2021	519.68	506.26	13.42	30.40	0.44	down
6/24/2021	529.51	506.12	23.39	30.40	0.77	down
7/14/2021	519.99	506.59	13.40	30.40	0.44	down
			Middle of screen elevation APW04			508.8
			Middle of screen elevation APW10			478.4

TABLE 3-2. VERTICAL HYDRAULIC GRADIENTS

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER STATION
PRIMARY ASH POND
NEWTON, IL

Date	APW03 Groundwater Elevation (ft NAVD88)	APW09 Groundwater Elevation (ft NAVD88)	Head Change (ft)	Distance Change [1] (ft)	Vertical Hydraulic Gradient [2] (dh/dl)	
	PMP	UA				
2/15/2021	523.58	504.93	18.65	47.00	0.40	down
3/9/2021	524.93	505.10	19.83	47.00	0.42	down
3/29/2021	526.00	505.23	20.77	47.00	0.44	down
4/27/2021	524.25	504.74	19.51	47.00	0.42	down
5/25/2021	523.85	- - -	- - -	- - -	- - -	- - -
6/15/2021	523.41	504.63	18.78	47.00	0.40	down
6/24/2021	523.18	504.48	18.70	47.00	0.40	down
7/14/2021	523.70	505.24	18.46	47.00	0.39	down
			Middle of screen elevation APW03			518.7
			Middle of screen elevation APW09			471.7

[O:SSW 09/09/21; U:SSW 08/31/21; C: LDC 08/31/21]

Notes:

[1] Distance change was calculated using the midpoint of the piezometer screen and water table surface. If the water table surface was above the top of the monitoring well screen, then distance change was calculated using the midpoint of both screens.

[2] Vertical gradients between ±0.0015 are considered flat, and typically have less than 0.02 foot difference in groundwater elevation between wells.

- - - = no data collected on date / no vertical gradient calculated
dh = head change
dl = distance change
ft = foot/feet
LCU = lower confining unit
NAVD88 = North American Vertical Datum of 1988
PMP = potential migration pathway
UA = uppermost aquifer

TABLE 3-3. FIELD HYDRAULIC CONDUCTIVITIES

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER STATION
PRIMARY ASH POND
NEWTON, ILLINOIS

Well ID	Gradient Position	Bottom of Screen Elevation (ft NAVD88)	Screen Length [1] (ft)	Field Identified Screened Material	Slug Type	Analysis Method	Falling Head (Slug In) K (cm/s)			Rising Head (Slug Out) K (cm/s)			Minimum Hydraulic Conductivity (cm/s)	Maximum Hydraulic Conductivity (cm/s)	Hydraulic Conductivity Geometric Mean (cm/s)
							1	2	3	1	2	3			
Upper Drift Unit/Potential Migration Pathway															
APW5S	U	521.05	10	SP	Solid	C-B-P	8.9E-04	7.4E-04	▨	6.1E-04	8.5E-04	▨	6.1E-04	1.5E-02	3.1E-03
APW12	U	513.33	10	SP	Solid	C-B-P	1.3E-02	9.8E-03	▨	1.3E-02	1.5E-02	▨			
Uppermost Aquifer															
APW11	U	471.05	5	SP-SC/GP	Solid	KGS Model	6.8E-03	5.9E-03	▨	3.5E-03	7.8E-03	▨	2.0E-04	1.5E-01	6.8E-03
APW13	D	471.66	5	SM	Solid	C-B-P	1.6E-03	1.5E-03	3.3E-03	3.8E-03	3.4E-03	▨			
APW14	D	468.85	5	SC	Solid	KGS Model	3.9E-03	4.3E-03	▨	3.2E-04	3.2E-04	2.8E-03			
APW15	D	419.06	5	SP-SM	Solid	KGS Model	4.9E-04	2.0E-04	1.4E-01	1.5E-01	1.5E-01	▨			
APW16	D	443.66	5	SP	Solid	B-Z	1.24E-01	1.41E-01	▨	7.60E-02	7.96E-02	▨			
APW17	D	437.84	5	(SW)g/(SP)g	Solid	C-B-P	1.13E-01	1.15E-02	▨	▨	▨	▨			
APW18	D	460.55	5	(SW)g/SC	Solid	C-B-P	2.67E-04	▨	▨	▨	▨	▨			
Ash Pond															
XPW01	CCR	531.62	10	(SW)g	Solid	Bouwer-Rice	1.8E-01	1.3E-02	▨	2.4E-02	1.4E-02	▨	1.0E-03	2.3E-01	2.0E-02
XPW02	CCR	535.97	10	(SW)g	Solid	Bouwer-Rice	2.0E-03	2.6E-03	▨	▨	▨	▨			
XPW03	CCR	530.81	10	(SW)g/SP	Solid	Bouwer-Rice	5.7E-02	7.2E-02	2.3E-01	1.5E-01	1.2E-01	1.4E-01			
XPW04	CCR	531.90	10	(SW)g	Solid	KGS Model	▨	2.1E-03	▨	1.2E-03	1.0E-03	▨			

[O: SSW 7/1/20; U:SSW 8/20/21; C:LDC 08/31/21]

Notes:

[1] All wells are constructed from 2 inch PVC with 0.01 inch slotted screens.

Test not analyzed/performed
B-Z = Butler-Zhan Test Solution
C-B-P = Cooper-Bredehoeft-Papadopulos Slug Test Solution
CCR = coal combustion residuals
cm/s = centimeters per second
D = downgradient
ft = foot/feet
K = hydraulic conductivity
KGS = Kansas Geological Survey
NAVD88 = North American Vertical Datum of 1988
U = upgradient

USCS = Unified Soil Classification System
GP = Poorly Graded Gravel
SC = Clayey Sand
SM = Silty Sand
SP = Poorly Graded Sand
SP-SC = Poorly Graded Sand to Clayey Sand
SP-SM = Poorly Graded Sand with Silt
(SW)g = Well Graded Sand with Gravel

TABLE 3-4. HORIZONTAL HYDRAULIC GRADIENTS AND GROUNDWATER FLOW VELOCITIES

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER STATION
PRIMARY ASH POND
NEWTON, IL

$V = K i \; / \; n_e$

V = Groundwater Velocity
K = Hydraulic Conductivity [1]
i = hydraulic gradient
n_e = Effective Porosity [2]

East-West Across CCR Unit (APW10 to APW17): Uppermost Aquifer

Distance between Wells (ft):	5941	
Hydraulic Conductivity (ft/day):	181	
Effective Porosity (%):	24%	Assumes: sand and silt

Date	APW10 Groundwater Elevation (ft NAVD88)	APW17 Groundwater Elevation (ft NAVD88)	Change in Elevation (ft)	Horizontal Gradient (ft/ft)	Velocity [3] (ft/day)
2/15/2021	506.65	492.02	14.63	0.0025	1.86
3/9/2021	506.84	491.74	15.10	0.0025	1.91
3/29/2021	506.94	491.95	14.99	0.0025	1.90
4/27/2021	506.53	491.87	14.66	0.0025	1.86
6/15/2021	506.26	491.57	14.69	0.0025	1.86
6/24/2021	506.12	491.52	14.60	0.0025	1.85
7/14/2021	506.59	491.58	15.01	0.0025	1.90
			Average	0.0025	1.88

North-South Across Northeastern Portion CCR Unit (APW05 to APW10): Uppermost Aquifer

Distance between Wells (ft):	3260	
Hydraulic Conductivity (ft/day):	1.4	
Effective Porosity (%):	24%	Assumes: sand and silt

Date	APW05 Groundwater Elevation (ft NAVD88)	APW10 Groundwater Elevation (ft NAVD88)	Change in Elevation (ft)	Horizontal Gradient (ft/ft)	Velocity [3] (ft/day)
2/15/2021	529.83	506.65	23.18	0.0071	0.04
3/9/2021	529.61	506.84	22.77	0.0070	0.04
3/29/2021	529.68	506.94	22.74	0.0070	0.04
4/27/2021	529.73	506.53	23.20	0.0071	0.04
5/24/2021	529.51	506.35	23.16	0.0071	0.04
6/15/2021	529.42	506.26	23.16	0.0071	0.04
6/24/2021	529.38	506.12	23.26	0.0071	0.04
7/14/2021	529.33	506.59	22.74	0.0070	0.04
			Average	0.0071	0.04

[O:SSW 7/15/21; U:SSW 8/19/21; C:LDC 8/31/21]

TABLE 3-4. HORIZONTAL HYDRAULIC GRADIENTS AND GROUNDWATER FLOW VELOCITIES

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER STATION
PRIMARY ASH POND
NEWTON, IL

Notes:

[1] Hydraulic conductivity values used above are average of the individual wells used in each velocity calculation as derived from slug tests completed in August 2015 and March and April 2021 by Ramboll.

[2] Effective porosity used in these calculations was derived from an average between estimated values of 0.20 for silt materials, 0.267 for gravel, 0.07 for clay, and 0.28 for sand from Morris, D.A. and A.I. Johnson, 1967. Summary of hydrologic and physical properties of rock and soil materials as analyzed by the Hydrologic Laboratory of the U.S. Geological Surve, U.S. Geological Survey Water-Supply Paper 1839-D, 42p. and Heath, R.C., 1983. Basic ground-water hydrology, U.S. Geological Survey Water-Supply Paper 2220, 86p. Effective porosity may be as high as maximum total porosity (50%) calculated in Table 2-1.

% = percent
ft= foot/feet
ft/ft = feet per foot
ft/day = feet per day
NAVD88 = North American Vertical Datum of 1988
NM = not measured

TABLE 4-1. GROUNDWATER ANALYTICAL RESULTS
HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, ILLINOIS

Location	Sample Date	Antimony, total (mg/L)	Arsenic, total (mg/L)	Barium, total (mg/L)	Beryllium, total (mg/L)	Boron, total (mg/L)	Cadmium, total (mg/L)	Calcium, total (mg/L)	Chloride, total (mg/L)	Chromium, total (mg/L)	Cobalt, total (mg/L)	Fluoride, total (mg/L)	Lead, total (mg/L)	Lithium, total (mg/L)	Mercury, total (mg/L)	Molybdenum, total (mg/L)	pH (field) (SU)	Radium 226 and 228 combined (pCi/L)	Selenium, total (mg/L)	Sulfate, total (mg/L)	Thallium, total (mg/L)	Total Dissolved Solids (mg/L)
35 I.A.C. 845.600	Lower	0	0	0	0	0	0	--	0	0	0	0	0	0	0	0	6.5	0	0	0	0	0
	Upper	0.006	0.010	2.0	0.004	2	0.005	--	200	0.1	0.006	4.0	0.0075	0.04	0.002	0.1	9.0	5	0.05	400	0.002	1200
APW02	01/13/2015	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	6.9	--	--	--	--	4800
APW02	04/21/2015	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	6.9	--	--	--	--	5300
APW02	07/15/2015	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	7.0	--	--	--	--	5200
APW02	10/07/2015	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	6.7	--	--	--	--	5000
APW02	02/17/2021	<0.003	<0.001	0.0084	<0.001	0.091	<0.001	430	84	<0.004	<0.002	<0.25	<0.001	0.079	<0.0002	<0.001	6.6	0.305	<0.001	2900	<0.001	4800
APW02	03/10/2021	<0.003	0.001	0.0091	<0.001	0.14	<0.001	530	120	<0.004	<0.002	<0.25	<0.001	0.11	<0.0002	0.0014	7.0	0.248	<0.001	3200	<0.001	5100
APW02	03/30/2021	<0.003	<0.001	0.0075	<0.001	0.24	<0.001	490	110	<0.004	<0.002	<0.25	<0.001	0.12	<0.0002	<0.001	6.6	0.193	<0.001	3100	<0.001	5200
APW02	04/29/2021	<0.003	<0.001	0.013	<0.001	0.12	<0.001	490	130	<0.004	<0.002	<0.25	<0.001	0.11	<0.0002	<0.001	6.7	0.924	<0.001	1500	<0.001	5100
APW02	05/25/2021	<0.003	<0.001	0.015	<0.001	0.14	<0.001	520	120	<0.004	<0.002	<0.25	<0.001	0.12	<0.0002	0.0011	6.7	1.01	<0.001	3200	<0.001	5200
APW02	06/16/2021	<0.003	<0.001	0.022	<0.001	0.16	<0.001	540	110	<0.004	<0.002	<0.25	<0.001	0.12	<0.0002	<0.001	6.6	0.34	<0.001	3100	<0.001	5000
APW02	06/30/2021	<0.003	<0.001	0.036	<0.001	0.49	<0.001	510	110	<0.004	<0.002	<0.25	<0.001	0.3	<0.0002	<0.001	6.6	0.618	<0.001	3200	<0.001	4900
APW02	07/15/2021	<0.003	<0.001	0.025	<0.001	0.14	<0.001	480	120	<0.004	<0.002	<0.25	<0.001	0.21	<0.0002	<0.001	6.6	0.33	<0.001	3100	<0.001	5400
APW03	01/13/2015	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	7.4	--	--	--	--	3000
APW03	04/20/2015	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	7.0	--	--	--	--	580
APW03	07/15/2015	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	6.9	--	--	--	--	580
APW03	10/07/2015	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	7.3	--	--	--	--	680
APW03	02/18/2021	<0.003	<0.001	0.077	<0.001	0.42	<0.00089	120	8.1	<0.004	<0.002	0.276	0.0013	0.022	0.0006	0.0018	6.7	0.126	<0.001	180	<0.001	620
APW03	03/10/2021	<0.003	<0.001	0.073	<0.001	0.4	<0.001	110	8.7	<0.004	<0.002	<0.25	<0.001	0.024	<0.0002	0.0014	7.2	0.238	<0.001	180	<0.001	720
APW03	03/31/2021	<0.003	<0.001	0.07	<0.001	0.44	<0.001	110	8.6	<0.004	<0.002	<0.25	<0.001	<0.02	<0.0002	0.0012	6.3	0.246	<0.001	170	<0.001	720
APW03	04/29/2021	<0.003	<0.001	0.068	<0.001	0.4	<0.001	110	8.2	<0.004	<0.002	<0.25	<0.001	<0.02	<0.0002	0.0019	7.0	0.822	<0.001	170	<0.001	660
APW03	05/25/2021	<0.003	<0.001	0.063	<0.001	0.38	<0.001	110	8	<0.004	<0.002	<0.25	<0.001	0.023	<0.0002	0.0015	7.0	0.369	<0.001	170	<0.001	760
APW03	06/17/2021	<0.003	<0.001	0.081	<0.001	0.45	<0.001	120	8.3	<0.004	<0.002	<0.25	<0.001	0.02	<0.0002	0.0014	7.0	0.461	<0.001	170	<0.001	660

TABLE 4-1. GROUNDWATER ANALYTICAL RESULTS
HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, ILLINOIS

Location	Sample Date	Antimony, total (mg/L)	Arsenic, total (mg/L)	Barium, total (mg/L)	Beryllium, total (mg/L)	Boron, total (mg/L)	Cadmium, total (mg/L)	Calcium, total (mg/L)	Chloride, total (mg/L)	Chromium, total (mg/L)	Cobalt, total (mg/L)	Fluoride, total (mg/L)	Lead, total (mg/L)	Lithium, total (mg/L)	Mercury, total (mg/L)	Molybdenum, total (mg/L)	pH (field) (SU)	Radium 226 and 228 combined (pCi/L)	Selenium, total (mg/L)	Sulfate, total (mg/L)	Thallium, total (mg/L)	Total Dissolved Solids (mg/L)
35 I.A.C. 845.600	Lower	0	0	0	0	0	0	--	0	0	0	0	0	0	0	0	6.5	0	0	0	0	0
	Upper	0.006	0.010	2.0	0.004	2	0.005	--	200	0.1	0.006	4.0	0.0075	0.04	0.002	0.1	9.0	5	0.05	400	0.002	1200
APW03	06/30/2021	<0.003	<0.001	0.059	<0.001	0.66	<0.001	110	11	<0.004	<0.002	<0.25	<0.001	0.035	<0.0002	0.0014	7.0	0.0646	<0.001	160	<0.001	600
APW03	07/15/2021	<0.003	<0.001	0.067	<0.001	0.49	<0.001	110	8.5	<0.004	<0.002	<0.25	<0.001	0.03	<0.0002	0.0013	6.9	1.03	<0.001	190	<0.001	710
APW04	01/13/2015	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	7.2	--	--	--	--	2300
APW04	04/20/2015	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	7.0	--	--	--	--	3100
APW04	07/15/2015	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	7.0	--	--	--	--	2400
APW04	10/07/2015	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	7.0	--	--	--	--	2300
APW04	02/18/2021	<0.003	0.0012	0.021	<0.001	0.033	<0.00089	230	36	<0.004	<0.002	<0.25	0.0014	0.022	0.001	<0.001	6.5	0.391	<0.001	860	<0.001	1700
APW04	03/11/2021	<0.003	0.0012	0.022	<0.001	0.024	<0.001	220	33	<0.004	<0.002	<0.25	0.001	0.024	<0.0002	<0.001	6.9	0.104	<0.001	970	<0.001	1800
APW04	03/31/2021	<0.003	<0.001	0.018	<0.001	0.031	<0.001	210	37	<0.004	<0.002	<0.25	<0.001	0.021	<0.0002	<0.001	6.1	0.0836	<0.001	960	<0.001	2000
APW04	04/29/2021	<0.003	<0.001	0.013	<0.001	0.023	<0.001	220	29	<0.004	<0.002	<0.25	<0.001	<0.02	<0.0002	<0.001	6.9	0.0843	<0.001	990	<0.001	1800
APW04	05/25/2021	<0.003	0.0014	0.026	<0.001	0.027	<0.001	220	32	<0.004	<0.002	<0.25	0.0014	0.021	<0.0002	<0.001	6.9	0.0127	<0.001	900	<0.001	1800
APW04	06/17/2021	<0.003	0.0012	0.026	<0.001	0.025	<0.001	240	29	<0.004	<0.002	<0.25	<0.001	0.021	<0.0002	<0.001	6.8	0.488	<0.001	950	<0.001	1800
APW04	06/30/2021	<0.003	<0.001	0.032	<0.001	0.21	<0.001	220	27	<0.004	<0.002	<0.25	<0.001	0.045	<0.0002	<0.001	6.8	0.663	<0.001	910	<0.001	1700
APW04	07/15/2021	<0.003	0.0012	0.025	<0.001	0.033	<0.001	210	34	<0.004	<0.002	<0.25	<0.001	0.034	<0.0002	<0.001	6.8	1.29	<0.001	920	<0.001	1900
APW05	12/15/2015	<0.003	0.018	0.19	<0.001	0.099	<0.001	51	48	<0.004	<0.002	0.486	0.0017	0.023	<0.0002	0.023	7.5	0.311	<0.001	15	<0.001	560
APW05	01/20/2016	<0.003	0.017	0.19	<0.001	0.12	<0.001	52	50	<0.004	<0.002	0.409	0.0016	0.017	0.0002	0.023	7.5	0.235	<0.001	15	<0.001	510
APW05	04/27/2016	<0.003	0.021	0.24	<0.001	0.1	<0.001	71	58	<0.004	<0.002	0.494	0.0012	0.02	0.002	0.032	7.7	0.281	0.001	14	<0.001	520
APW05	08/01/2016	<0.003	0.014	0.21	<0.001	0.1	<0.001	49	52	<0.004	<0.002	0.54	<0.001	0.016	<0.0002	0.027	7.5	0.616	<0.001	1.8	<0.001	500
APW05	10/25/2016	<0.003	0.013	0.22	<0.001	0.12	<0.001	50	50	<0.004	<0.002	0.66	<0.001	0.015	<0.0002	0.027	7.6	0.654	<0.001	<1	<0.001	1000
APW05	01/23/2017	<0.003	0.015	0.21	<0.001	0.09	<0.001	45	50	<0.004	<0.002	0.418	<0.001	0.013	<0.0002	0.021	7.4	0.0999	<0.001	<1	<0.001	550
APW05	04/24/2017	<0.003	0.014	0.2	<0.001	0.079	<0.001	44	46	0.004	<0.002	0.437	0.0014	0.015	<0.0002	0.016	7.0	1.19	<0.001	1.2	<0.001	600
APW05	06/13/2017	<0.003	0.016	0.23	<0.001	0.082	<0.001	48	47	<0.004	<0.002	0.508	<0.001	0.014	<0.0002	0.018	7.1	1.32	<0.001	<1	<0.001	540

TABLE 4-1. GROUNDWATER ANALYTICAL RESULTS

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, ILLINOIS

Location	Sample Date	Antimony, total (mg/L)	Arsenic, total (mg/L)	Barium, total (mg/L)	Beryllium, total (mg/L)	Boron, total (mg/L)	Cadmium, total (mg/L)	Calcium, total (mg/L)	Chloride, total (mg/L)	Chromium, total (mg/L)	Cobalt, total (mg/L)	Fluoride, total (mg/L)	Lead, total (mg/L)	Lithium, total (mg/L)	Mercury, total (mg/L)	Molybdenum, total (mg/L)	pH (field) (SU)	Radium 226 and 228 combined (pCi/L)	Selenium, total (mg/L)	Sulfate, total (mg/L)	Thallium, total (mg/L)	Total Dissolved Solids (mg/L)
35 I.A.C. 845.600	Lower	0	0	0	0	0	0	--	0	0	0	0	0	0	0	0	6.5	0	0	0	0	0
	Upper	0.006	0.010	2.0	0.004	2	0.005	--	200	0.1	0.006	4.0	0.0075	0.04	0.002	0.1	9.0	5	0.05	400	0.002	1200
APW05	11/17/2017	--	--	--	--	0.099	--	51	43	--	--	0.634	--	--	--	--	6.9	--	--	<1	--	480
APW05	05/18/2018	--	--	--	--	0.1	--	48	48	--	--	0.525	--	--	--	--	7.1	--	--	2.1	--	480
APW05	08/17/2018	--	--	--	--	--	--	54	56	--	--	--	--	--	--	--	7.0	--	--	1.4	--	--
APW05	11/09/2018	--	--	--	--	0.098	--	50	51	--	--	0.427	--	--	--	--	7.0	--	--	5.1	--	500
APW05	02/22/2019	--	--	--	--	0.11	--	50	48	--	--	0.374	--	--	--	--	6.9	--	--	3.5	--	600
APW05	08/22/2019	--	--	--	--	0.12	--	49	50	--	--	<0.25	--	--	--	--	7.0	--	--	2.3	--	530
APW05	02/04/2020	--	--	--	--	0.091	--	51	54	--	--	0.48	--	--	--	--	7.5	--	--	2.3	--	600
APW05	06/11/2020	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	7.4	--	--	--	--	--
APW05	07/28/2020	--	--	--	--	0.1	--	53	52	--	--	0.544	--	--	--	--	7.7	--	--	1.8	--	530
APW05	02/09/2021	--	--	--	--	0.13	--	54	50	--	--	0.543	--	--	--	--	7.6	--	--	1.3	--	560
APW05	02/17/2021	<0.003	0.003	0.22	<0.001	0.1	<0.001	49	52	<0.004	<0.002	0.479	<0.001	<0.02	<0.0002	0.019	7.2	0.356	<0.001	3.3	<0.001	510
APW05	03/10/2021	<0.003	0.022	0.24	<0.001	0.12	<0.001	55	48	<0.004	<0.002	0.365	<0.001	<0.02	<0.0002	0.011	7.7	0.872	<0.001	1.3	<0.001	530
APW05	03/30/2021	<0.003	0.022	0.27	<0.001	0.092	<0.001	54	49	<0.004	<0.002	0.342	<0.001	<0.02	<0.0002	0.011	7.2	1.31	<0.001	1.3	<0.001	560
APW05	04/28/2021	<0.003	0.018	0.24	<0.001	0.099	<0.001	52	51	<0.004	<0.002	0.514	<0.001	<0.02	<0.0002	0.012	7.5	0.932	<0.001	1.1	<0.001	570
APW05	05/25/2021	<0.003	0.019	0.24	<0.001	0.12	<0.001	54	48	<0.004	<0.002	0.532	<0.001	<0.02	<0.0002	0.012	7.5	1.04	<0.001	1	<0.001	570
APW05	06/17/2021	<0.003	0.022	0.25	<0.001	0.091	<0.001	58	50	<0.004	<0.002	0.516	<0.001	<0.02	<0.0002	0.011	7.7	1.08	<0.001	<1	<0.001	560
APW05	06/30/2021	<0.003	0.021	0.25	<0.001	0.26	<0.001	52	51	<0.004	<0.002	0.441	<0.001	<0.02	<0.0002	0.011	7.6	0.0954	<0.001	1	<0.001	470
APW05	07/15/2021	<0.003	0.022	0.25	<0.001	0.1	<0.001	51	52	<0.004	<0.002	0.386	<0.001	<0.02	<0.0002	0.011	7.8	0.305	<0.001	1.1	<0.001	560
APW05S	02/17/2021	<0.003	<0.001	0.048	<0.001	0.04	<0.001	390	550	<0.004	0.0058	0.345	<0.001	0.043	<0.0002	0.0027	6.6	0.191	<0.001	640	<0.001	3700
APW05S	03/10/2021	<0.003	<0.001	0.051	<0.001	0.13	<0.001	420	190	<0.004	0.0025	0.379	<0.001	0.042	<0.0002	0.0016	7.0	0.195	<0.001	200	<0.001	3600
APW05S	04/29/2021	<0.003	0.0018	0.048	<0.001	0.04	<0.001	420	200	<0.004	<0.002	0.373	<0.001	0.039	<0.0002	0.0014	6.8	0.146	<0.001	2000	<0.001	3800
APW05S	05/25/2021	<0.003	0.0016	0.053	<0.001	0.056	<0.001	420	210	<0.004	<0.002	0.391	<0.001	0.042	<0.0002	0.0014	6.9	0.386	<0.001	2100	<0.001	3500

TABLE 4-1. GROUNDWATER ANALYTICAL RESULTS

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, ILLINOIS

Location	Sample Date	Antimony, total (mg/L)	Arsenic, total (mg/L)	Barium, total (mg/L)	Beryllium, total (mg/L)	Boron, total (mg/L)	Cadmium, total (mg/L)	Calcium, total (mg/L)	Chloride, total (mg/L)	Chromium, total (mg/L)	Cobalt, total (mg/L)	Fluoride, total (mg/L)	Lead, total (mg/L)	Lithium, total (mg/L)	Mercury, total (mg/L)	Molybdenum, total (mg/L)	pH (field) (SU)	Radium 226 and 228 combined (pCi/L)	Selenium, total (mg/L)	Sulfate, total (mg/L)	Thallium, total (mg/L)	Total Dissolved Solids (mg/L)
35 I.A.C. 845.600	Lower	0	0	0	0	0	0	--	0	0	0	0	0	0	0	0	6.5	0	0	0	0	0
	Upper	0.006	0.010	2.0	0.004	2	0.005	--	200	0.1	0.006	4.0	0.0075	0.04	0.002	0.1	9.0	5	0.05	400	0.002	1200
APW05S	06/17/2021	<0.003	0.0022	0.051	<0.001	0.043	<0.001	410	190	<0.004	0.0022	0.364	<0.001	0.038	<0.0002	0.0013	6.8	1.58	<0.001	2100	<0.001	3600
APW05S	06/30/2021	<0.003	0.002	0.051	<0.001	0.046	<0.001	380	180	<0.004	0.0022	0.401	<0.001	0.091	<0.0002	0.0011	6.7	0.29	<0.001	1900	<0.001	3200
APW05S	07/15/2021	<0.003	0.0026	0.05	<0.001	0.039	<0.001	370	260	<0.004	0.0027	0.379	<0.001	0.067	<0.0002	0.0011	6.8	0.644	<0.001	2000	<0.001	3800
APW06	12/15/2015	<0.003	0.017	0.16	<0.001	0.073	<0.001	53	26	<0.004	<0.002	0.509	<0.001	0.019	0.00023	0.012	7.5	0.591	0.006	9.9	<0.001	480
APW06	01/20/2016	<0.003	0.0091	0.17	<0.001	0.082	<0.001	53	24	<0.004	<0.002	0.393	<0.001	0.012	<0.0002	0.013	7.4	0.236	<0.001	9.9	<0.001	500
APW06	04/27/2016	<0.003	0.019	0.21	<0.001	0.16	<0.001	64	29	<0.004	<0.002	0.564	0.0012	0.019	<0.0002	0.028	6.5	0.984	<0.001	7.4	<0.001	450
APW06	08/01/2016	<0.003	0.0045	0.2	<0.001	0.078	<0.001	50	27	<0.004	<0.002	0.65	<0.001	0.016	<0.0002	0.0066	7.4	0.69	<0.001	1.2	<0.001	520
APW06	10/25/2016	<0.003	0.0041	0.22	<0.001	0.093	<0.001	50	26	<0.004	<0.002	0.686	<0.001	0.015	<0.0002	0.0087	7.5	0.329	<0.001	<1	<0.001	560
APW06	01/23/2017	<0.003	0.0036	0.21	<0.001	0.076	<0.001	46	26	<0.004	<0.002	0.448	<0.001	0.014	<0.0002	0.0086	6.9	0.316	<0.001	<1	<0.001	530
APW06	04/24/2017	<0.003	0.0042	0.2	<0.001	0.074	0.0012	43	50	<0.004	<0.002	0.47	0.0012	0.015	<0.0002	0.011	7.2	0.859	<0.001	<1	0.0011	540
APW06	06/13/2017	<0.003	0.0057	0.22	0.0025	0.093	0.0017	51	25	<0.004	0.002	0.567	0.0025	0.014	<0.0002	0.014	7.1	0.932	0.0014	2.3	0.0025	460
APW06	11/17/2017	--	--	--	--	0.094	--	50	23	--	--	0.617	--	--	--	--	7.2	--	--	1.9	--	470
APW06	05/18/2018	--	--	--	--	0.087	--	51	25	--	--	0.564	--	--	--	--	7.3	--	--	1.7	--	420
APW06	08/17/2018	--	--	--	--	--	--	52	25	--	--	--	--	--	--	--	7.3	--	--	1.7	--	--
APW06	11/09/2018	--	--	--	--	0.083	--	51	24	--	--	0.459	--	--	--	--	7.2	--	--	2.1	--	440
APW06	02/22/2019	--	--	--	--	0.09	--	45	24	--	--	0.386	--	--	--	--	7.3	--	--	1.7	--	480
APW06	08/23/2019	--	--	--	--	0.11	--	55	26	--	--	0.314	--	--	--	--	7.3	--	--	5.8	--	500
APW06	02/04/2020	--	--	--	--	0.08	--	53	27	--	--	0.483	--	--	--	--	7.5	--	--	<1	--	640
APW06	06/11/2020	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	7.4	--	--	--	--	--
APW06	07/28/2020	--	--	--	--	0.091	--	55	24	--	--	0.564	--	--	--	--	7.8	--	--	3.2	--	510
APW06	02/09/2021	--	--	--	--	0.087	--	55	24	--	--	0.585	--	--	--	--	7.6	--	--	1.8	--	450
APW06	02/17/2021	<0.003	0.0045	0.24	<0.001	0.086	<0.001	54	23	<0.004	<0.002	0.504	<0.001	<0.02	<0.0002	0.0073	6.4	0.231	<0.001	3.6	<0.001	500

TABLE 4-1. GROUNDWATER ANALYTICAL RESULTS
HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, ILLINOIS

Location	Sample Date	Antimony, total (mg/L)	Arsenic, total (mg/L)	Barium, total (mg/L)	Beryllium, total (mg/L)	Boron, total (mg/L)	Cadmium, total (mg/L)	Calcium, total (mg/L)	Chloride, total (mg/L)	Chromium, total (mg/L)	Cobalt, total (mg/L)	Fluoride, total (mg/L)	Lead, total (mg/L)	Lithium, total (mg/L)	Mercury, total (mg/L)	Molybdenum, total (mg/L)	pH (field) (SU)	Radium 226 and 228 combined (pCi/L)	Selenium, total (mg/L)	Sulfate, total (mg/L)	Thallium, total (mg/L)	Total Dissolved Solids (mg/L)
35 I.A.C. 845.600	Lower	0	0	0	0	0	0	--	0	0	0	0	0	0	0	0	6.5	0	0	0	0	0
	Upper	0.006	0.010	2.0	0.004	2	0.005	--	200	0.1	0.006	4.0	0.0075	0.04	0.002	0.1	9.0	5	0.05	400	0.002	1200
APW06	03/10/2021	<0.003	0.0052	0.25	<0.001	0.086	<0.001	58	22	<0.004	<0.002	0.427	<0.001	<0.02	<0.0002	0.0058	7.7	0.594	<0.001	9.2	<0.001	540
APW06	03/30/2021	<0.003	0.0052	0.22	<0.001	0.078	<0.001	56	26	<0.004	<0.002	0.368	<0.001	<0.02	<0.0002	0.0062	7.1	4.9	<0.001	7.7	<0.001	500
APW06	04/29/2021	<0.003	0.0073	0.25	<0.001	0.082	<0.001	62	23	0.0068	0.0027	0.496	0.0032	<0.02	<0.0002	0.0077	7.7	1.55	<0.001	8.5	<0.001	610
APW06	05/25/2021	<0.003	0.0088	0.28	<0.001	0.1	<0.001	68	23	0.011	0.0043	0.55	0.0074	<0.02	<0.0002	0.0085	7.7	0.474	<0.001	7.8	<0.001	490
APW06	06/16/2021	<0.003	0.0081	0.25	<0.001	0.11	<0.001	67	25	0.0076	0.0033	0.545	0.0066	<0.02	<0.0002	0.0083	7.7	1.35	<0.001	6.2	<0.001	520
APW06	06/30/2021	<0.003	0.0078	0.23	<0.001	0.085	<0.001	63	32	0.0058	0.0033	0.481	0.0063	0.03	<0.0002	0.0078	7.6	0.544	<0.001	6.3	<0.001	500
APW06	07/15/2021	<0.003	0.0067	0.23	<0.001	0.083	<0.001	55	27	<0.004	<0.002	0.442	0.0013	<0.02	<0.0002	0.0076	7.5	0.285	<0.001	7.8	<0.001	490
APW07	12/15/2015	<0.003	0.0039	0.35	<0.001	0.073	<0.001	74	69	<0.004	<0.002	0.467	<0.001	<0.01	<0.0002	0.014	7.4	1.16	<0.001	13	<0.001	520
APW07	01/21/2016	<0.003	0.0065	0.4	<0.001	0.052	<0.001	74	79	<0.004	<0.002	0.38	0.0015	<0.01	<0.0002	0.0083	7.4	1.06	<0.001	8.6	<0.001	440
APW07	05/03/2016	<0.003	0.004	0.41	<0.001	0.071	<0.001	85	72	<0.004	<0.002	0.545	<0.001	<0.01	<0.0002	0.0086	7.5	1.74	<0.001	7.5	<0.001	500
APW07	08/01/2016	<0.003	0.0049	0.45	<0.001	0.07	<0.001	86	77	<0.004	<0.002	0.462	<0.001	<0.01	<0.0002	0.006	7.3	1.32	<0.001	2.8	<0.001	490
APW07	10/26/2016	<0.003	0.0058	0.5	<0.001	0.096	<0.001	76	79	<0.004	<0.002	0.425	<0.001	<0.01	<0.0002	0.0054	7.2	2.02	<0.001	<1	<0.001	590
APW07	01/26/2017	<0.003	0.0062	0.45	<0.001	0.082	<0.001	87	77	<0.004	<0.002	0.352	<0.001	<0.01	<0.0002	0.0072	7.2	1.82	<0.001	<1	<0.001	520
APW07	04/24/2017	<0.003	0.0077	0.45	<0.001	0.069	<0.001	87	77	0.0049	<0.002	0.367	0.0022	<0.01	<0.0002	0.0029	7.3	1.26	<0.001	<1	<0.001	600
APW07	06/13/2017	<0.003	0.0087	0.48	<0.001	0.084	<0.001	93	77	<0.004	<0.002	0.425	0.0046	<0.01	<0.0002	0.0039	7.2	1.69	<0.001	<1	<0.001	560
APW07	11/17/2017	--	--	--	--	0.097	--	72	73	--	--	0.508	--	--	--	--	7.2	--	--	3.8	--	530
APW07	05/18/2018	--	--	--	--	0.082	--	97	75	--	--	0.435	--	--	--	--	7.1	--	--	4.9	--	500
APW07	08/18/2018	--	--	--	--	--	--	100	77	--	--	--	--	--	--	--	7.1	--	--	3.2	--	--
APW07	11/09/2018	--	--	--	--	0.08	--	92	71	--	--	0.343	--	--	--	--	7.0	--	--	4.5	--	500
APW07	02/22/2019	--	--	--	--	0.06	--	45	43	--	--	0.734	--	--	--	--	7.2	--	--	66	--	340
APW07	08/23/2019	--	--	--	--	0.075	--	58	46	--	--	0.632	--	--	--	--	7.1	--	--	62	--	350
APW07	02/05/2020	--	--	--	--	0.092	--	100	68	--	--	0.332	--	--	--	--	7.4	--	--	5.7	--	640

TABLE 4-1. GROUNDWATER ANALYTICAL RESULTS

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, ILLINOIS

Location	Sample Date	Antimony, total (mg/L)	Arsenic, total (mg/L)	Barium, total (mg/L)	Beryllium, total (mg/L)	Boron, total (mg/L)	Cadmium, total (mg/L)	Calcium, total (mg/L)	Chloride, total (mg/L)	Chromium, total (mg/L)	Cobalt, total (mg/L)	Fluoride, total (mg/L)	Lead, total (mg/L)	Lithium, total (mg/L)	Mercury, total (mg/L)	Molybdenum, total (mg/L)	pH (field) (SU)	Radium 226 and 228 combined (pCi/L)	Selenium, total (mg/L)	Sulfate, total (mg/L)	Thallium, total (mg/L)	Total Dissolved Solids (mg/L)
35 I.A.C. 845.600	Lower	0	0	0	0	0	0	--	0	0	0	0	0	0	0	0	6.5	0	0	0	0	0
	Upper	0.006	0.010	2.0	0.004	2	0.005	--	200	0.1	0.006	4.0	0.0075	0.04	0.002	0.1	9.0	5	0.05	400	0.002	1200
APW07	06/11/2020	--	--	--	--	--	--	--	68	--	--	--	--	--	--	--	7.3	--	--	--	--	--
APW07	07/28/2020	--	--	--	--	0.086	--	94	77	--	--	0.412	--	--	--	--	7.3	--	--	6.7	--	530
APW07	02/10/2021	--	--	--	--	0.11	--	110	69	--	--	0.372	--	--	--	--	7.0	--	--	6.3	--	540
APW08	12/15/2015	<0.003	0.0083	0.24	<0.001	0.083	<0.001	85	52	<0.004	<0.002	0.441	0.0016	0.013	<0.0002	0.0075	7.4	1.95	<0.001	35	<0.001	560
APW08	01/21/2016	<0.003	0.016	0.3	<0.001	0.06	<0.001	85	59	0.0049	<0.002	0.414	0.0023	0.012	<0.0002	0.0055	7.5	2.27	<0.001	34	<0.001	510
APW08	05/03/2016	<0.003	0.012	0.32	<0.001	0.083	<0.001	100	55	0.0045	<0.002	0.566	0.0021	<0.01	<0.0002	0.0063	7.4	1.88	0.0016	30	<0.001	560
APW08	08/02/2016	<0.003	0.013	0.32	<0.001	0.076	<0.001	94	56	<0.004	<0.002	0.504	<0.001	<0.01	<0.0002	0.0054	7.2	0.857	<0.001	35	<0.001	520
APW08	10/26/2016	<0.003	0.013	0.35	<0.001	0.091	<0.001	84	59	<0.004	<0.002	0.463	<0.001	<0.01	<0.0002	0.0055	7.4	0.812	<0.001	37	<0.001	600
APW08	01/25/2017	<0.003	0.017	0.37	<0.001	0.081	<0.001	100	57	<0.004	<0.002	0.404	<0.001	<0.01	<0.0002	0.0057	7.2	0.499	<0.001	36	<0.001	600
APW08	04/25/2017	<0.003	0.02	0.36	<0.001	0.073	<0.001	100	57	0.016	0.0056	0.418	0.0097	0.017	<0.0002	0.0074	7.5	1.8	<0.001	38	<0.001	590
APW08	06/13/2017	<0.003	0.017	0.39	<0.001	0.092	<0.001	110	57	0.01	0.0043	0.449	0.0075	0.012	<0.0002	0.0081	7.3	2.08	<0.001	38	<0.001	600
APW08	11/17/2017	--	--	--	--	0.11	--	83	50	--	--	0.474	--	--	--	--	7.1	--	--	39	--	490
APW08	05/18/2018	--	--	--	--	0.088	--	92	56	--	--	0.448	--	--	--	--	7.2	--	--	37	--	520
APW08	08/18/2018	--	--	--	--	--	--	82	57	--	--	--	--	--	--	--	7.2	--	--	43	--	--
APW08	11/09/2018	--	--	--	--	0.086	--	110	56	--	--	0.373	--	--	--	--	7.1	--	--	42	--	580
APW08	02/22/2019	--	--	--	--	0.1	--	80	56	--	--	0.393	--	--	--	--	7.2	--	--	46	--	600
APW08	08/23/2019	--	--	--	--	0.1	--	82	59	--	--	0.337	--	--	--	--	7.2	--	--	48	--	570
APW08	02/05/2020	--	--	--	--	0.1	--	120	55	--	--	0.331	--	--	--	--	7.4	--	--	45	--	700
APW08	06/11/2020	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	7.3	--	--	--	--	--
APW08	07/28/2020	--	--	--	--	0.087	--	110	62	--	--	0.441	--	--	--	--	7.3	--	--	47	--	620
APW08	10/28/2020	--	--	--	--	--	--	--	55	--	--	--	--	--	--	--	7.4	--	--	--	--	--
APW08	02/10/2021	--	--	--	--	0.11	--	110	57	--	--	<0.25	--	--	--	--	7.2	--	--	42	--	550

TABLE 4-1. GROUNDWATER ANALYTICAL RESULTS

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, ILLINOIS

Location	Sample Date	Antimony, total (mg/L)	Arsenic, total (mg/L)	Barium, total (mg/L)	Beryllium, total (mg/L)	Boron, total (mg/L)	Cadmium, total (mg/L)	Calcium, total (mg/L)	Chloride, total (mg/L)	Chromium, total (mg/L)	Cobalt, total (mg/L)	Fluoride, total (mg/L)	Lead, total (mg/L)	Lithium, total (mg/L)	Mercury, total (mg/L)	Molybdenum, total (mg/L)	pH (field) (SU)	Radium 226 and 228 combined (pCi/L)	Selenium, total (mg/L)	Sulfate, total (mg/L)	Thallium, total (mg/L)	Total Dissolved Solids (mg/L)
35 I.A.C. 845.600	Lower	0	0	0	0	0	0	--	0	0	0	0	0	0	0	0	6.5	0	0	0	0	0
	Upper	0.006	0.010	2.0	0.004	2	0.005	--	200	0.1	0.006	4.0	0.0075	0.04	0.002	0.1	9.0	5	0.05	400	0.002	1200
APW09	12/15/2015	<0.003	0.007	0.24	<0.001	0.062	<0.001	54	88	<0.004	<0.002	0.574	0.0011	<0.01	<0.0002	0.021	7.5	0.612	<0.001	25	<0.001	630
APW09	01/20/2016	<0.003	0.0067	0.24	<0.001	0.074	<0.001	57	95	<0.004	<0.002	0.468	0.0044	<0.01	<0.0002	0.023	7.6	0.743	<0.001	27	<0.001	540
APW09	05/03/2016	<0.003	0.008	0.32	<0.001	0.07	<0.001	70	110	<0.004	<0.002	0.746	0.0051	<0.01	<0.0002	0.021	7.6	1.54	<0.001	18	<0.001	590
APW09	08/02/2016	<0.003	0.014	0.41	<0.001	0.073	<0.001	74	130	<0.004	<0.002	0.532	<0.001	<0.01	<0.0002	0.011	7.2	1.137	<0.001	4.2	<0.001	640
APW09	10/26/2016	<0.003	0.016	0.47	<0.001	0.09	<0.001	77	130	<0.004	<0.002	0.528	<0.001	<0.01	<0.0002	0.01	7.6	1.18	<0.001	1.5	<0.001	770
APW09	01/25/2017	<0.003	0.018	0.44	<0.001	0.081	<0.001	79	130	<0.004	<0.002	0.468	<0.001	<0.01	<0.0002	0.0075	7.5	1.78	<0.001	<1	<0.001	740
APW09	04/25/2017	<0.003	0.017	0.38	<0.001	0.078	<0.001	67	120	<0.004	<0.002	0.515	<0.001	<0.01	0.00023	0.0053	7.5	1.07	<0.001	1.1	<0.001	840
APW09	06/13/2017	<0.003	0.0039	0.11	<0.001	0.053	<0.001	42	51	<0.004	<0.002	0.755	<0.001	<0.01	<0.0002	0.016	7.5	0.984	<0.001	48	<0.001	300
APW09	11/18/2017	--	--	--	--	0.08	--	68	84	--	--	0.655	--	--	--	--	7.4	--	--	4.5	--	720
APW09	05/18/2018	--	--	--	--	0.098	--	80	120	--	--	0.467	--	--	--	--	7.4	--	--	1	--	710
APW09	08/17/2018	--	--	--	--	--	--	81	130	--	--	--	--	--	--	--	7.5	--	--	2.4	--	--
APW09	11/09/2018	--	--	--	--	0.055	--	44	44	--	--	0.73	--	--	--	--	7.4	--	--	62	--	300
APW09	02/22/2019	--	--	--	--	0.054	--	38	47	--	--	0.714	--	--	--	--	7.5	--	--	61	--	320
APW09	08/23/2019	--	--	--	--	0.055	--	41	51	--	--	0.621	--	--	--	--	7.4	--	--	51	--	360
APW09	02/19/2020	--	--	--	--	0.1	--	88	130	--	--	0.453	--	--	--	--	7.5	--	--	7.5	--	790
APW09	06/11/2020	--	--	--	--	--	--	--	130	--	--	--	--	--	--	--	7.4	--	--	--	--	870
APW09	07/28/2020	--	--	--	--	0.1	--	84	140	--	--	0.537	--	--	--	--	7.4	--	--	3.2	--	810
APW09	02/11/2021	--	--	--	--	0.11	--	85	140	--	--	0.536	--	--	--	--	7.4	--	--	<10	--	840
APW10	12/16/2015	<0.003	0.0034	0.038	<0.001	0.066	<0.001	120	46	<0.004	<0.002	0.328	<0.001	0.03	<0.0002	0.0094	7.1	0.755	<0.001	430	<0.001	1000
APW10	01/20/2016	<0.003	0.0043	0.042	<0.001	0.077	<0.001	120	48	<0.004	<0.002	<0.25	<0.001	0.021	<0.0002	0.011	7.2	1.16	<0.001	410	<0.001	950
APW10	05/03/2016	<0.003	0.0083	0.04	<0.001	0.065	<0.001	140	46	<0.004	<0.002	0.448	<0.001	0.023	<0.0002	0.01	7.1	0.799	<0.001	410	<0.001	930
APW10	08/02/2016	<0.003	0.0092	0.037	<0.001	0.063	<0.001	140	45	<0.004	<0.002	0.367	<0.001	0.026	<0.0002	0.0091	7.1	0.6	<0.001	410	<0.001	840

TABLE 4-1. GROUNDWATER ANALYTICAL RESULTS

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, ILLINOIS

Location	Sample Date	Antimony, total (mg/L)	Arsenic, total (mg/L)	Barium, total (mg/L)	Beryllium, total (mg/L)	Boron, total (mg/L)	Cadmium, total (mg/L)	Calcium, total (mg/L)	Chloride, total (mg/L)	Chromium, total (mg/L)	Cobalt, total (mg/L)	Fluoride, total (mg/L)	Lead, total (mg/L)	Lithium, total (mg/L)	Mercury, total (mg/L)	Molybdenum, total (mg/L)	pH (field) (SU)	Radium 226 and 228 combined (pCi/L)	Selenium, total (mg/L)	Sulfate, total (mg/L)	Thallium, total (mg/L)	Total Dissolved Solids (mg/L)
35 I.A.C. 845.600	Lower	0	0	0	0	0	0	--	0	0	0	0	0	0	0	0	6.5	0	0	0	0	0
	Upper	0.006	0.010	2.0	0.004	2	0.005	--	200	0.1	0.006	4.0	0.0075	0.04	0.002	0.1	9.0	5	0.05	400	0.002	1200
APW10	10/26/2016	<0.003	0.009	0.04	<0.001	0.069	<0.001	120	48	<0.004	<0.002	0.371	<0.001	0.027	<0.0002	0.0093	7.1	0.556	<0.001	470	<0.001	960
APW10	01/25/2017	<0.003	0.01	0.035	<0.001	0.065	<0.001	160	46	<0.004	<0.002	0.258	<0.001	0.023	<0.0002	0.0085	7.1	0.43	<0.001	430	<0.001	1000
APW10	04/25/2017	<0.003	0.0084	0.031	<0.001	0.056	<0.001	120	44	<0.004	<0.002	0.289	<0.001	0.026	<0.0002	0.0071	7.0	0.604	<0.001	410	<0.001	1000
APW10	06/13/2017	<0.003	0.0035	0.027	<0.001	0.077	<0.001	110	46	<0.004	<0.002	0.344	<0.001	0.026	<0.0002	0.0091	6.9	0.897	<0.001	410	<0.001	920
APW10	11/18/2017	--	--	--	--	0.072	--	120	47	--	--	0.414	--	--	--	--	6.9	--	--	390	--	910
APW10	05/18/2018	--	--	--	--	0.08	--	130	51	--	--	0.335	--	--	--	--	7.2	--	--	440	--	900
APW10	08/17/2018	--	--	--	--	--	--	130	51	--	--	--	--	--	--	--	6.9	--	--	420	--	--
APW10	11/09/2018	--	--	--	--	0.078	--	140	47	--	--	0.281	--	--	--	--	7.0	--	--	410	--	900
APW10	02/22/2019	--	--	--	--	0.079	--	110	50	--	--	0.276	--	--	--	--	6.9	--	--	420	--	990
APW10	08/23/2019	--	--	--	--	0.096	--	130	50	--	--	0.359	--	--	--	--	7.0	--	--	390	--	1000
APW10	02/05/2020	--	--	--	--	0.094	--	140	44	--	--	<0.25	--	--	--	--	7.1	--	--	400	--	1200
APW10	06/11/2020	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	7.2	--	--	--	--	1000
APW10	07/28/2020	--	--	--	--	0.076	--	140	53	--	--	0.356	--	--	--	--	7.1	--	--	410	--	1000
APW10	02/11/2021	--	--	--	--	0.082	--	150	45	--	--	0.362	--	--	--	--	7.4	--	--	410	--	1100
APW10	06/17/2021	<0.003	0.008	0.026	<0.001	0.07	<0.001	150	47	<0.004	<0.002	0.436	<0.001	0.022	<0.0002	0.0074	7.3	0.617	<0.001	540	<0.001	1100
APW10	06/30/2021	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	7.5	--	--	--	--	1000
APW10	07/29/2021	<0.003	0.0058	0.026	<0.001	0.075	<0.001	150	45	<0.004	<0.002	0.462	<0.001	0.022	<0.0002	0.0071	7.5	0.794	<0.001	410	<0.001	1000
APW11	02/18/2021	<0.003	0.002	0.16	<0.001	0.074	<0.00089	96	47	<0.004	<0.002	0.497	<0.001	0.021	0.00042	0.013	6.1	1.87	<0.001	280	<0.001	780
APW11	03/09/2021	<0.003	0.0046	0.077	<0.001	0.075	<0.001	120	26	0.0086	0.0029	<0.25	0.0076	0.024	<0.0002	0.0078	7.2	0.763	0.001	290	<0.001	940
APW11	03/29/2021	<0.003	0.005	0.071	<0.001	0.15	<0.001	130	26	0.012	0.0048	<0.25	0.014	0.028	<0.0002	0.0059	6.6	2.13	0.0032	270	<0.001	820
APW11	04/28/2021	<0.003	0.0021	0.048	<0.001	0.066	<0.001	120	26	<0.004	<0.002	<0.25	<0.001	0.021	<0.0002	0.0046	7.1	0.477	<0.001	280	<0.001	920
APW11	05/24/2021	<0.003	0.0015	0.05	<0.001	0.083	<0.001	130	27	<0.004	<0.002	<0.25	<0.001	0.024	0.00082	0.005	7.4	0.563	<0.001	300	0.0036	850

TABLE 4-1. GROUNDWATER ANALYTICAL RESULTS
HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, ILLINOIS

Location	Sample Date	Antimony, total (mg/L)	Arsenic, total (mg/L)	Barium, total (mg/L)	Beryllium, total (mg/L)	Boron, total (mg/L)	Cadmium, total (mg/L)	Calcium, total (mg/L)	Chloride, total (mg/L)	Chromium, total (mg/L)	Cobalt, total (mg/L)	Fluoride, total (mg/L)	Lead, total (mg/L)	Lithium, total (mg/L)	Mercury, total (mg/L)	Molybdenum, total (mg/L)	pH (field) (SU)	Radium 226 and 228 combined (pCi/L)	Selenium, total (mg/L)	Sulfate, total (mg/L)	Thallium, total (mg/L)	Total Dissolved Solids (mg/L)
35 I.A.C. 845.600	Lower	0	0	0	0	0	0	--	0	0	0	0	0	0	0	0	6.5	0	0	0	0	0
	Upper	0.006	0.010	2.0	0.004	2	0.005	--	200	0.1	0.006	4.0	0.0075	0.04	0.002	0.1	9.0	5	0.05	400	0.002	1200
APW11	06/16/2021	<0.003	0.002	0.047	<0.001	0.078	<0.001	130	26	<0.004	<0.002	0.375	<0.001	0.024	<0.0002	0.0048	7.2	2.05	<0.001	290	<0.001	850
APW11	06/30/2021	<0.003	0.0018	0.042	<0.001	0.065	<0.001	120	33	<0.004	<0.002	0.409	<0.001	0.038	<0.0002	0.0044	7.1	0.382	<0.001	280	<0.001	860
APW11	07/15/2021	<0.003	0.0023	0.042	<0.001	0.062	<0.001	120	31	<0.004	<0.002	<0.25	<0.001	0.03	<0.0002	0.0043	7.2	0.474	<0.001	140	<0.001	810
APW12	02/17/2021	<0.003	0.0016	0.058	<0.001	0.27	<0.00089	230	27	<0.004	0.0073	<0.25	<0.001	0.033	0.0019	0.0037	6.2	0.682	<0.001	390	<0.001	1300
APW12	03/09/2021	<0.003	0.0017	0.05	<0.001	0.26	<0.001	230	27	<0.004	0.0073	<0.25	<0.001	0.028	<0.0002	0.0025	6.5	0.367	<0.001	480	<0.001	1300
APW12	03/29/2021	<0.003	0.002	0.046	<0.001	0.29	<0.001	220	28	<0.004	0.0065	<0.25	<0.001	0.029	<0.0002	0.0019	6.0	0.166	<0.001	440	<0.001	1400
APW12	04/28/2021	<0.003	0.0016	0.038	<0.001	0.21	<0.001	210	23	<0.004	0.005	<0.25	<0.001	0.026	<0.0002	0.0012	6.4	0.234	<0.001	390	<0.001	1300
APW12	05/25/2021	<0.003	0.0023	0.038	<0.001	0.29	<0.001	220	23	<0.004	0.0043	<0.25	<0.001	0.029	<0.0002	0.0038	6.5	0.319	<0.001	390	<0.001	1300
APW12	06/16/2021	<0.003	0.0027	0.039	<0.001	0.15	<0.001	210	20	<0.004	0.0034	<0.25	<0.001	0.026	<0.0002	<0.001	6.4	1.88	<0.001	290	<0.001	1100
APW12	06/30/2021	<0.003	0.0019	0.04	<0.001	0.11	<0.001	190	20	<0.004	0.0032	<0.25	<0.001	0.046	<0.0002	<0.001	6.3	0.466	<0.001	310	<0.001	990
APW12	07/15/2021	<0.003	0.0017	0.033	<0.001	0.28	<0.001	210	26	<0.004	0.0032	<0.25	<0.001	0.045	<0.0002	<0.001	6.5	0.667	<0.001	440	<0.001	1300
APW13	02/22/2021	<0.003	0.0043	0.055	<0.001	0.12	<0.001	110	57	<0.004	<0.002	0.503	<0.001	0.042	<0.0002	0.016	7.1	0.429	<0.001	220	<0.001	760
APW13	03/10/2021	<0.003	0.0046	0.054	<0.001	0.11	<0.001	120	71	<0.004	<0.002	0.326	<0.001	0.044	<0.0002	0.017	7.2	0.17	<0.001	210	<0.001	850
APW13	03/31/2021	<0.003	0.0047	0.057	<0.001	0.12	<0.001	110	46	<0.004	<0.002	0.43	<0.001	0.041	<0.0002	0.011	6.4	1.05	<0.001	210	<0.001	880
APW13	04/29/2021	<0.003	0.0046	0.05	<0.001	0.11	<0.001	110	48	<0.004	<0.002	0.327	<0.001	0.032	<0.0002	0.011	7.2	1.44	<0.001	210	<0.001	840
APW13	05/25/2021	<0.003	0.0031	0.051	<0.001	0.12	<0.001	120	64	<0.004	<0.002	0.402	<0.001	0.03	<0.0002	0.0096	7.3	0.966	<0.001	220	<0.001	880
APW13	06/17/2021	<0.003	0.0037	0.051	<0.001	0.1	<0.001	130	53	<0.004	<0.002	0.487	<0.001	0.027	<0.0002	0.0089	7.2	0.281	<0.001	220	<0.001	830
APW13	06/30/2021	<0.003	0.0039	0.051	<0.001	0.11	<0.001	120	45	<0.004	<0.002	0.447	<0.001	0.054	<0.0002	0.0088	7.3	0.546	<0.001	230	<0.001	790
APW13	07/15/2021	<0.003	0.006	0.05	<0.001	0.15	<0.001	110	55	<0.004	<0.002	<0.25	<0.001	0.036	<0.0002	0.0082	7.3	0.328	<0.001	210	<0.001	820
APW14	02/22/2021	<0.003	0.0074	0.14	<0.001	0.11	<0.001	120	55	0.0057	0.0023	0.489	0.0032	0.051	<0.0002	0.014	7.5	0.752	<0.001	320	<0.001	830
APW14	03/10/2021	<0.003	0.0095	0.099	<0.001	0.097	<0.001	130	65	<0.004	<0.002	0.313	0.002	0.044	<0.0002	0.0083	7.4	0.356	<0.001	340	<0.001	970
APW14	03/31/2021	<0.003	0.0098	0.092	<0.001	0.11	<0.001	130	46	<0.004	<0.002	0.363	<0.001	0.034	<0.0002	0.0068	6.5	0.594	<0.001	330	<0.001	1000

TABLE 4-1. GROUNDWATER ANALYTICAL RESULTS

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, ILLINOIS

Location	Sample Date	Antimony, total (mg/L)	Arsenic, total (mg/L)	Barium, total (mg/L)	Beryllium, total (mg/L)	Boron, total (mg/L)	Cadmium, total (mg/L)	Calcium, total (mg/L)	Chloride, total (mg/L)	Chromium, total (mg/L)	Cobalt, total (mg/L)	Fluoride, total (mg/L)	Lead, total (mg/L)	Lithium, total (mg/L)	Mercury, total (mg/L)	Molybdenum, total (mg/L)	pH (field) (SU)	Radium 226 and 228 combined (pCi/L)	Selenium, total (mg/L)	Sulfate, total (mg/L)	Thallium, total (mg/L)	Total Dissolved Solids (mg/L)
35 I.A.C. 845.600	Lower	0	0	0	0	0	0	--	0	0	0	0	0	0	0	0	6.5	0	0	0	0	0
	Upper	0.006	0.010	2.0	0.004	2	0.005	--	200	0.1	0.006	4.0	0.0075	0.04	0.002	0.1	9.0	5	0.05	400	0.002	1200
APW14	04/28/2021	<0.003	0.0053	0.1	<0.001	0.093	<0.001	130	44	<0.004	<0.002	<0.25	<0.001	0.03	<0.0002	0.0081	7.4	0.342	<0.001	320	<0.001	1000
APW14	05/25/2021	<0.003	0.0047	0.098	<0.001	0.11	<0.001	130	43	<0.004	<0.002	0.358	<0.001	0.029	<0.0002	0.0063	7.5	0.658	<0.001	320	<0.001	920
APW14	06/17/2021	<0.003	0.0054	0.086	<0.001	0.089	<0.001	140	45	<0.004	<0.002	0.436	<0.001	0.024	<0.0002	0.0053	7.4	1.26	<0.001	310	<0.001	940
APW14	06/30/2021	<0.003	0.0061	0.082	<0.001	0.097	<0.001	150	49	<0.004	<0.002	0.371	<0.001	0.047	<0.0002	0.0053	7.5	1.05	<0.001	330	<0.001	860
APW14	07/15/2021	<0.003	0.0055	0.07	<0.001	0.12	<0.001	130	53	<0.004	<0.002	<0.25	<0.001	0.032	<0.0002	0.0046	7.4	0.695	<0.001	330	<0.001	970
APW15	02/23/2021	<0.003	0.02	0.56	<0.001	0.14	<0.001	93	260	<0.004	<0.002	0.544	0.0011	<0.02	<0.0002	0.0089	7.0	1.43	<0.001	<1	<0.001	1100
APW15	03/10/2021	<0.003	0.022	0.61	<0.001	0.13	<0.001	100	250	<0.004	<0.002	1.65	0.0012	<0.02	<0.0002	0.016	7.2	2.88	<0.001	<1	<0.001	1100
APW15	03/31/2021	<0.003	0.016	0.63	<0.001	0.16	<0.001	100	240	0.005	0.0021	1.44	0.003	<0.02	<0.0002	0.013	6.5	1.76	<0.001	<1	<0.001	1100
APW15	04/28/2021	<0.003	0.021	0.6	<0.001	0.13	<0.001	96	230	<0.004	<0.002	1.81	<0.001	<0.02	<0.0002	0.015	7.2	1.17	<0.001	<1	<0.001	1200
APW15	05/24/2021	<0.003	0.017	0.57	<0.001	0.15	<0.001	98	230	<0.004	<0.002	1.68	<0.001	<0.02	<0.0002	0.012	7.3	1.87	<0.001	<1	<0.001	1000
APW15	06/17/2021	<0.003	0.017	0.6	<0.001	0.13	<0.001	95	240	<0.004	<0.002	3.18	<0.001	0.022	<0.0002	0.012	7.3	2.54	<0.001	<1	<0.001	1000
APW15	06/30/2021	<0.003	0.017	0.6	<0.001	0.13	<0.001	98	230	<0.004	<0.002	2.89	<0.001	0.022	<0.0002	0.0098	7.1	2.46	<0.001	<1	<0.001	1000
APW15	07/14/2021	<0.003	0.016	0.6	<0.001	0.16	<0.001	96	130	<0.004	<0.002	8.16	<0.001	<0.02	<0.0002	0.0094	7.2	2.23	<0.001	<1	<0.001	1200
APW16	02/23/2021	<0.003	0.014	0.62	<0.001	0.14	<0.001	92	71	<0.004	<0.002	0.629	<0.001	<0.02	<0.0002	0.0036	7.4	2.08	<0.001	1.9	<0.001	780
APW16	03/10/2021	<0.003	0.015	0.66	<0.001	0.15	<0.001	99	71	<0.004	<0.002	0.755	<0.001	<0.02	<0.0002	0.0044	7.5	2.17	<0.001	<1	<0.001	750
APW16	03/30/2021	<0.003	0.013	0.66	<0.001	0.17	<0.001	97	71	<0.004	<0.002	0.886	<0.001	<0.02	<0.0002	0.0033	7.0	0.946	<0.001	<1	<0.001	740
APW16	04/28/2021	<0.003	0.0083	0.62	<0.001	0.12	<0.001	96	75	<0.004	<0.002	0.742	<0.001	<0.02	<0.0002	0.0015	7.4	1.55	<0.001	<1	<0.001	750
APW16	05/24/2021	<0.003	0.0074	0.61	<0.001	0.15	<0.001	100	74	<0.004	<0.002	0.639	<0.001	<0.02	<0.0002	0.0012	7.6	1.19	<0.001	<1	<0.001	810
APW16	06/16/2021	<0.003	0.0077	0.57	<0.001	0.14	<0.001	100	73	<0.004	<0.002	0.735	<0.001	<0.02	<0.0002	<0.001	7.4	2.05	<0.001	<1	<0.001	720
APW16	06/30/2021	<0.003	0.0083	0.55	<0.001	0.13	<0.001	96	59	<0.004	<0.002	0.766	<0.001	<0.02	<0.0002	<0.001	7.0	5.85	<0.001	<1	<0.001	610
APW16	07/15/2021	<0.003	0.0088	0.56	<0.001	0.13	<0.001	95	77	<0.004	<0.002	0.55	<0.001	<0.02	<0.0002	<0.001	7.4	2.91	<0.001	<1	<0.001	690
APW17	02/23/2021	<0.003	0.0033	0.54	<0.001	0.091	<0.001	100	64	<0.004	<0.002	0.944	<0.001	<0.02	<0.0002	0.0085	7.4	0.821	<0.001	34	<0.001	680

TABLE 4-1. GROUNDWATER ANALYTICAL RESULTS
HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, ILLINOIS

Location	Sample Date	Antimony, total (mg/L)	Arsenic, total (mg/L)	Barium, total (mg/L)	Beryllium, total (mg/L)	Boron, total (mg/L)	Cadmium, total (mg/L)	Calcium, total (mg/L)	Chloride, total (mg/L)	Chromium, total (mg/L)	Cobalt, total (mg/L)	Fluoride, total (mg/L)	Lead, total (mg/L)	Lithium, total (mg/L)	Mercury, total (mg/L)	Molybdenum, total (mg/L)	pH (field) (SU)	Radium 226 and 228 combined (pCi/L)	Selenium, total (mg/L)	Sulfate, total (mg/L)	Thallium, total (mg/L)	Total Dissolved Solids (mg/L)
35 I.A.C. 845.600	Lower	0	0	0	0	0	0	--	0	0	0	0	0	0	0	0	6.5	0	0	0	0	0
	Upper	0.006	0.010	2.0	0.004	2	0.005	--	200	0.1	0.006	4.0	0.0075	0.04	0.002	0.1	9.0	5	0.05	400	0.002	1200
APW17	03/10/2021	<0.003	0.0026	0.57	<0.001	0.083	<0.001	110	60	<0.004	<0.002	0.677	<0.001	<0.02	<0.0002	0.0066	7.7	0.849	<0.001	30	<0.001	650
APW17	03/30/2021	<0.003	0.0014	0.63	<0.001	0.086	<0.001	110	57	<0.004	<0.002	0.374	<0.001	<0.02	<0.0002	0.0052	7.1	0.259	<0.001	31	<0.001	620
APW17	04/29/2021	<0.003	0.003	0.6	<0.001	0.088	<0.001	120	55	<0.004	<0.002	0.468	<0.001	<0.02	<0.0002	0.0055	7.4	1.51	<0.001	36	<0.001	630
APW17	05/24/2021	<0.003	0.0035	0.59	<0.001	0.087	<0.001	110	88	<0.004	<0.002	0.474	<0.001	<0.02	<0.0002	0.005	7.4	1.36	<0.001	40	<0.001	670
APW17	06/16/2021	<0.003	0.0058	0.62	<0.001	0.088	<0.001	120	54	<0.004	<0.002	0.593	<0.001	<0.02	<0.0002	0.0048	7.4	3.11	<0.001	40	<0.001	640
APW17	06/30/2021	<0.003	0.0074	0.61	<0.001	0.084	<0.001	110	49	<0.004	<0.002	0.548	<0.001	<0.02	<0.0002	0.0048	7.4	2.6	<0.001	41	<0.001	630
APW17	07/15/2021	<0.003	0.0083	0.61	<0.001	0.091	<0.001	110	31	<0.004	<0.002	0.412	<0.001	<0.02	<0.0002	0.0049	7.4	1.55	<0.001	<25	<0.001	650
APW18	02/23/2021	<0.003	0.0043	0.18	<0.001	0.12	<0.001	49	79	0.0085	0.0034	1.43	0.0079	<0.02	<0.0002	0.033	7.9	2.72	<0.001	26	<0.001	560
APW18	03/10/2021	<0.003	0.0032	0.36	<0.001	0.11	<0.001	62	42	0.0066	0.0024	6.38	0.0048	<0.02	<0.0002	0.015	7.8	1.88	<0.001	12	<0.001	610
APW18	03/30/2021	<0.003	0.0025	0.34	<0.001	0.15	<0.001	60	35	<0.004	<0.002	7.02	0.0023	<0.02	<0.0002	0.012	7.3	0.912	<0.001	9.4	0.0016	580
APW18	04/29/2021	<0.003	0.0019	0.34	<0.001	0.14	<0.001	60	40	<0.004	<0.002	0.617	0.0018	<0.02	<0.0002	0.016	7.6	2.4	<0.001	<1	<0.001	490
APW18	05/24/2021	<0.003	0.0014	0.35	<0.001	0.11	<0.001	59	35	<0.004	<0.002	0.597	<0.001	<0.02	<0.0002	0.0095	7.6	1.91	<0.001	<1	<0.001	650
APW18	06/16/2021	0.0035	0.0043	0.36	0.0033	0.19	0.0034	64	29	0.0042	0.0036	6.67	0.0035	<0.02	0.00047	0.0096	7.6	2.12	0.0038	4.8	0.0022	550
APW18	06/30/2021	<0.003	<0.001	0.36	<0.001	0.11	<0.001	60	28	<0.004	<0.002	3.23	<0.001	<0.02	<0.0002	0.0048	7.6	1.73	<0.001	2.2	<0.001	450
APW18	07/15/2021	<0.003	0.0015	0.33	<0.001	0.12	<0.001	64	31	<0.004	<0.002	4.67	<0.001	<0.02	<0.0002	0.0051	7.6	2.2	<0.001	1.9	<0.001	520

Notes:
Detected at concentration greater than the GWPS
-- = data not available
GWPS = Groundwater Protection Standard
mg/L = milligrams per liter
pCi/L = picocuries per liter
SU = standard units
< = concentration is less than the concentration shown, which corresponds to the reporting limit for the method. Estimated concentrations below the reporting limit and associated qualifiers are not provided since they are not utilized in statistics to determine exceedances above Part 845 standards.
35 I.A.C. 845.600 = Residuals in Surface Impoundments: Title 35 of the Illinois Administrative Code § 845

TABLE 4-2. GROUNDWATER FIELD PARAMETERS

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, ILLINOIS

Sample Location	Sample Date	Dissolved Oxygen (mg/L)	Oxidation Reduction Potential (mV)	pH (field) (SU)	Specific Conductance (micromhos/cm)	Temperature (deg. C)	Turbidity (NTU)
APW02	01/13/2015	--	--	6.9	6190	--	--
APW02	04/21/2015	--	--	6.9	5320	--	--
APW02	07/15/2015	--	--	7.0	1653	--	--
APW02	10/07/2015	--	--	6.7	4290	--	--
APW02	02/17/2021	6.88	90.3	6.6	5409	5.9	22.1
APW02	03/10/2021	2.11	62.6	7.0	4714	12.4	57.5
APW02	03/30/2021	1.91	82	6.6	3158	13.6	20800
APW02	04/29/2021	1.10	164	6.7	5417	17.8	13.9
APW02	05/25/2021	1.10	116	6.7	5536	29.6	57
APW02	06/16/2021	0.57	52.9	6.6	5574	30.0	62.9
APW02	06/30/2021	0.86	82.3	6.6	5523	22.8	19
APW02	07/15/2021	0.51	57.6	6.5	5543	29.6	8.04
APW03	01/13/2015	--	--	7.4	1132	--	--
APW03	04/20/2015	--	--	7.0	988	--	--
APW03	07/15/2015	--	--	6.9	1212	--	--
APW03	10/07/2015	--	--	7.3	1047	--	--
APW03	02/18/2021	6.74	225	6.7	1132	7.9	140
APW03	03/10/2021	2.67	30.7	7.2	1041	12.6	55.8
APW03	03/31/2021	1.17	28.9	6.3	949.5	10.1	51.8
APW03	04/29/2021	0.92	114	7.0	1104	19.6	8.47
APW03	05/25/2021	1.10	132	7.0	1132	29.6	15.8
APW03	06/17/2021	0.81	166	7.0	1114	22.8	26.5
APW03	06/30/2021	0.85	37.8	7.0	1115	25.4	7.56
APW03	07/15/2021	0.78	-28.6	6.9	1121	35.0	124
APW04	01/13/2015	--	--	7.2	2980	--	--
APW04	04/20/2015	--	--	7.0	2880	--	--
APW04	07/15/2015	--	--	7.0	1431	--	--
APW04	10/07/2015	--	--	7.0	2510	--	--
APW04	02/18/2021	1.81	217	6.5	2396	6.9	293
APW04	03/11/2021	0.44	224	6.9	2387	10.6	62.9
APW04	03/31/2021	0.35	55	6.1	2005	10.8	63.4
APW04	04/29/2021	0.43	140	6.9	2297	19.0	8.29
APW04	05/25/2021	0.42	166	6.9	2313	22.7	56.7
APW04	06/17/2021	0.53	169	6.8	2330	27.0	31.4
APW04	06/30/2021	1.10	141	6.8	2339	26.4	25.9
APW04	07/15/2021	0.74	78.1	6.8	2333	33.9	227
APW05	12/15/2015	0	-57	7.5	1040	13.4	14.4
APW05	01/20/2016	0	-51	7.5	1030	12.6	44.6
APW05	04/27/2016	0	27	7.7	1120	14.3	15
APW05	08/01/2016	0	-64	7.5	1100	18.0	2.5
APW05	10/25/2016	0	-83	7.6	1070	16.8	0
APW05	01/23/2017	0	-143	7.4	1050	13.6	0
APW05	04/24/2017	0	-101	7.0	1060	17.3	0
APW05	06/13/2017	0	-88	7.1	1050	17.5	35.5

TABLE 4-2. GROUNDWATER FIELD PARAMETERS

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, ILLINOIS

Sample Location	Sample Date	Dissolved Oxygen (mg/L)	Oxidation Reduction Potential (mV)	pH (field) (SU)	Specific Conductance (micromhos/cm)	Temperature (deg. C)	Turbidity (NTU)
APW05	11/17/2017	0	-60	6.9	1080	12.7	24.2
APW05	05/18/2018	0	-61	7.1	1140	15.6	22.6
APW05	08/17/2018	0	-69	7.0	1025	15.2	22
APW05	11/09/2018	0	-56	7.0	1100	14.7	27.1
APW05	02/22/2019	0	-60	6.9	1071	11.4	34.6
APW05	08/22/2019	0	-60	7.0	1021	17.3	67.3
APW05	02/04/2020	0.83	-119	7.5	971.9	11.3	2.97
APW05	06/11/2020	1.20	-124	7.4	856	15.0	4.5
APW05	07/28/2020	1.20	-146	7.7	924.7	19.0	3.57
APW05	02/09/2021	0.19	-129	7.6	996	11.2	39.9
APW05	02/17/2021	1.33	192	7.2	1086	7.6	0
APW05	03/10/2021	0.15	-129	7.7	975.9	13.6	16.5
APW05	03/30/2021	0.69	-71.9	7.2	980.3	13.6	1.08
APW05	04/28/2021	0.60	-65	7.5	867	15.9	6.7
APW05	05/25/2021	0.95	61.8	7.5	976	17.9	1.89
APW05	06/17/2021	0.34	-150	7.7	946	18.8	0.81
APW05	06/30/2021	0.29	-160	7.5	977	19.0	1.02
APW05	07/15/2021	0.25	-140	7.8	995	16.7	3.96
APW05S	02/17/2021	0.69	202	6.6	4672	6.5	0
APW05S	03/10/2021	0.24	16.3	7.0	4186	12.5	0
APW05S	04/29/2021	0.45	4.7	6.8	4339	18.0	14.2
APW05S	05/25/2021	0.93	-37	6.9	4306	30.3	40.2
APW05S	06/17/2021	0.73	-8.8	6.8	3977	28.6	20.5
APW05S	06/30/2021	0.81	2.8	6.7	3967	27.6	32.6
APW05S	07/15/2021	0.73	-35.6	6.8	3933	32.6	9.27
APW06	12/15/2015	0	-5	7.5	915	13.2	1000
APW06	01/20/2016	0	58	7.4	990	11.9	77.4
APW06	04/27/2016	0	-61	6.5	896	14.4	0.3
APW06	08/01/2016	0	-80	7.4	1010	17.1	0
APW06	10/25/2016	0	-73	7.5	971	15.3	0
APW06	01/23/2017	0	-109	6.9	938	13.2	0
APW06	04/24/2017	0	-94	7.2	961	17.6	0
APW06	06/13/2017	0	-83	7.1	914	16.5	19.8
APW06	11/17/2017	0	-79	7.2	860	12.1	17.2
APW06	05/18/2018	0	-67	7.3	902	14.4	12.3
APW06	08/17/2018	0	-73	7.3	910	15.0	22.7
APW06	11/09/2018	0	-82	7.2	938	15.7	28.3
APW06	02/22/2019	0	-71	7.3	942	11.9	34.7
APW06	08/23/2019	0	-58	7.3	873	17.5	14.9
APW06	02/04/2020	2.20	-125	7.5	889.5	11.2	3.04
APW06	06/11/2020	1.30	-125	7.4	807	15.2	24.6
APW06	07/28/2020	0.66	-164	7.8	880.8	18.3	5.59
APW06	02/09/2021	1.40	-110	7.6	859.8	9.0	0.91
APW06	02/17/2021	0.19	-41	6.4	937.9	4.6	0

TABLE 4-2. GROUNDWATER FIELD PARAMETERS

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, ILLINOIS

Sample Location	Sample Date	Dissolved Oxygen (mg/L)	Oxidation Reduction Potential (mV)	pH (field) (SU)	Specific Conductance (micromhos/cm)	Temperature (deg. C)	Turbidity (NTU)
APW06	03/10/2021	0.23	-131	7.7	779.1	14.4	25.7
APW06	03/30/2021	0.31	-69.7	7.1	893.1	15.5	0
APW06	04/29/2021	0.36	-130	7.7	925	15.8	111
APW06	05/25/2021	0.29	-138	7.7	939	24.4	225
APW06	06/16/2021	0.47	-127	7.7	928	22.8	315
APW06	06/30/2021	0.78	-120	7.6	925	23.8	276
APW06	07/15/2021	0.75	-148	7.5	926	27.7	41.9
APW07	12/15/2015	1.71	-40	7.4	1060	12.0	55.1
APW07	01/21/2016	0	-110	7.4	1130	10.5	185
APW07	05/03/2016	0	-94	7.5	1210	13.5	179
APW07	08/01/2016	0	-114	7.3	1130	19.4	26
APW07	10/26/2016	0	-69	7.2	1110	17.9	5.7
APW07	01/26/2017	0	-136	7.2	1110	11.0	0
APW07	04/24/2017	0	-112	7.3	1130	17.2	0
APW07	06/13/2017	0	-94	7.2	1060	17.1	39.5
APW07	11/17/2017	0	-71	7.2	1120	12.5	47
APW07	05/18/2018	0	-88	7.1	1090	15.4	47.9
APW07	08/18/2018	0	-88	7.1	1000	15.0	41.1
APW07	11/09/2018	0	-92	7.0	993	13.9	33
APW07	02/22/2019	0	-92	7.2	1012	11.6	34
APW07	08/23/2019	0	-74	7.1	879	17.0	27.4
APW07	02/05/2020	0.39	-137	7.4	247.7	10.3	77.6
APW07	06/11/2020	0.16	-164	7.3	1112	15.1	51
APW07	07/28/2020	1.40	-104	7.3	1083	18.8	3.3
APW07	02/10/2021	2.30	-10.5	7.0	806.2	9.4	72.6
APW08	12/15/2015	0	38	7.4	1140	12.7	105
APW08	01/21/2016	0	-93	7.5	1150	11.0	83.3
APW08	05/03/2016	0	-93	7.4	1055	13.3	168
APW08	08/02/2016	0	-87	7.2	1160	17.9	5
APW08	10/26/2016	0	-76	7.4	1180	17.2	2.1
APW08	01/25/2017	0	-121	7.2	1140	14.2	0
APW08	04/25/2017	0	-103	7.5	1160	17.0	1000
APW08	06/13/2017	0	-108	7.3	1090	17.4	1000
APW08	11/17/2017	0	-102	7.1	1020	12.5	1000
APW08	05/18/2018	0	-96	7.2	940	16.2	890
APW08	08/18/2018	0	-101	7.2	993	15.0	100
APW08	11/09/2018	0	-109	7.1	857	13.8	1000
APW08	02/22/2019	0	-99	7.2	955	11.8	1000
APW08	08/23/2019	0	-98	7.2	1004	17.1	1000
APW08	02/05/2020	1.10	-130	7.4	1150	11.5	114
APW08	06/11/2020	0.54	-127	7.3	1163	15.1	30
APW08	07/28/2020	1.30	-101	7.3	1138	16.8	9.2
APW08	10/28/2020	1.00	-94.2	7.4	1148	14.2	17.9
APW08	02/10/2021	1.70	-103	7.2	1045	10.3	104

TABLE 4-2. GROUNDWATER FIELD PARAMETERS
HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, ILLINOIS

Sample Location	Sample Date	Dissolved Oxygen (mg/L)	Oxidation Reduction Potential (mV)	pH (field) (SU)	Specific Conductance (micromhos/cm)	Temperature (deg. C)	Turbidity (NTU)
APW09	12/15/2015	0	11	7.5	1150	13.0	11.7
APW09	01/20/2016	0	72	7.6	1040	11.3	49.6
APW09	05/03/2016	0	56	7.6	988	13.9	67.7
APW09	08/02/2016	0	-106	7.2	1460	17.2	0
APW09	10/26/2016	0	-77	7.6	1450	15.9	0
APW09	01/25/2017	0	-140	7.5	1470	14.8	0
APW09	04/25/2017	0	-74	7.5	1420	18.4	0
APW09	06/13/2017	0	-67	7.5	1390	17.1	27.4
APW09	11/18/2017	0	-78	7.4	1420	13.0	34.1
APW09	05/18/2018	0	-71	7.4	1490	15.2	35.1
APW09	08/17/2018	0	-69	7.5	1265	15.0	40
APW09	11/09/2018	0	-72	7.4	1240	16.7	48.5
APW09	02/22/2019	0	-65	7.5	1285	11.7	50.3
APW09	08/23/2019	0	-60	7.4	1180	16.6	29
APW09	02/19/2020	0.86	-151	7.5	1456	13.5	10.1
APW09	06/11/2020	0.60	-152	7.4	1516	15.7	389
APW09	07/28/2020	0.47	-136	7.4	1467	18.9	19.9
APW09	02/11/2021	2.00	-28.1	7.4	1208	9.4	31.8
APW10	12/16/2015	1.93	-29	7.1	1610	13.3	1000
APW10	01/20/2016	0	-21	7.2	1430	12.5	1000
APW10	05/03/2016	0	-19	7.1	1326	13.4	33.3
APW10	08/02/2016	0	-18	7.1	1640	17.4	0
APW10	10/26/2016	0	38	7.1	1600	14.5	0
APW10	01/25/2017	0	-73	7.1	1570	13.6	0
APW10	04/25/2017	0	0	7.0	1610	15.6	0
APW10	06/13/2017	0	12	6.9	1620	15.8	36.5
APW10	11/18/2017	0	34	6.9	1480	12.4	43
APW10	05/18/2018	0	29	7.2	1600	14.7	48.5
APW10	08/17/2018	0	57	6.9	1468	15.1	41.2
APW10	11/09/2018	0	78	7.0	1340	14.9	46.8
APW10	02/22/2019	0	61	6.9	1510	11.9	41.1
APW10	08/23/2019	0	69	7.0	1520	17.2	30.7
APW10	02/05/2020	0.50	14.7	7.1	356	10.6	4.57
APW10	06/11/2020	1.10	-207	7.2	1563	16.1	1.4
APW10	07/28/2020	0.21	-153	7.1	1546	20.8	1.6
APW10	02/11/2021	3.00	46.7	7.4	1594	5.9	168
APW10	06/17/2021	1.70	79.6	7.3	1501	20.4	2.24
APW10	06/30/2021	1.50	140	7.5	1531	16.2	5.8
APW10	07/29/2021	2.80	132	7.5	4100	19.1	0
APW11	02/18/2021	0.14	125	6.1	1285	9.8	0
APW11	03/09/2021	0.37	-56.2	7.2	1460	15.0	174
APW11	03/29/2021	0.23	2.6	6.6	1130	14.4	1760
APW11	04/28/2021	2.00	-51.6	7.1	1297	16.7	96.4
APW11	05/24/2021	3.10	-82.4	7.4	1337	16.5	11.3

TABLE 4-2. GROUNDWATER FIELD PARAMETERS
HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, ILLINOIS

Sample Location	Sample Date	Dissolved Oxygen (mg/L)	Oxidation Reduction Potential (mV)	pH (field) (SU)	Specific Conductance (micromhos/cm)	Temperature (deg. C)	Turbidity (NTU)
APW11	06/16/2021	2.60	-41.2	7.2	1320	19.9	14.8
APW11	06/30/2021	3.10	-37.2	7.1	381.5	17.4	3.65
APW11	07/15/2021	4.10	-24.4	7.2	1318	16.9	5.12
APW12	02/17/2021	0.16	27.2	6.2	1917	10.2	0
APW12	03/09/2021	0.15	45.5	6.5	2115	13.6	6.38
APW12	03/29/2021	0.20	117	6.0	1752	13.4	12.2
APW12	04/28/2021	0.92	11.2	6.4	1537	15.5	22.6
APW12	05/25/2021	0.84	49.5	6.5	1571	17.6	44.5
APW12	06/16/2021	2.40	9.9	6.4	268.4	22.4	10.7
APW12	06/30/2021	1.10	115	6.3	1546	17.6	3.59
APW12	07/15/2021	0.40	22.8	6.5	1870	17.1	3.16
APW13	02/22/2021	0.25	-102	7.1	1544	13.4	25.7
APW13	03/10/2021	0.31	-80.2	7.2	1336	13.8	28.7
APW13	03/31/2021	1.13	-9.4	6.4	1392	12.7	28.8
APW13	04/29/2021	1.40	-96.2	7.2	1399	15.9	8.6
APW13	05/25/2021	3.50	-95.6	7.3	1390	19.1	12.4
APW13	06/17/2021	1.90	-75.3	7.2	1399	18.9	1.69
APW13	06/30/2021	2.10	-78.8	7.3	1393	18.2	0
APW13	07/15/2021	1.50	-90	7.3	1237	16.9	3.97
APW14	02/22/2021	0.95	-113	7.5	1646	12.8	173
APW14	03/10/2021	0.29	-104	7.4	1251	13.7	57.1
APW14	03/31/2021	0.16	-46.7	6.5	1236	13.5	40.4
APW14	04/28/2021	0.99	-120	7.4	1504	17.0	51.6
APW14	05/25/2021	2.00	-145	7.5	1300	20.1	24.9
APW14	06/17/2021	2.60	-97.8	7.4	1313	17.3	19.3
APW14	06/30/2021	1.80	-123	7.5	1290	17.4	11.3
APW14	07/15/2021	0.73	-144	7.4	1533	19.5	4.81
APW15	02/23/2021	0.44	-98.5	7.0	2095	12.9	80.4
APW15	03/10/2021	1.03	-108	7.2	1648	14.9	134
APW15	03/31/2021	0.13	-61.8	6.5	184.7	13.3	126
APW15	04/28/2021	0.16	-122	7.2	2041	16.2	506
APW15	05/24/2021	1.70	-128	7.3	1955	18.8	23.5
APW15	06/17/2021	0.22	-136	7.3	2030	19.9	6.01
APW15	06/30/2021	0.90	-133	7.1	1926	18.2	7.5
APW15	07/14/2021	1.20	-142	7.2	1662	19.4	5.18
APW16	02/23/2021	3.16	-71.4	7.4	1162	12.1	9.52
APW16	03/10/2021	0.18	-132	7.5	1316	13.6	0
APW16	03/30/2021	0.22	-99.5	7.0	1318	13.5	0
APW16	04/28/2021	1.30	-129	7.4	1350	15.1	10.6
APW16	05/24/2021	2.40	-132	7.5	1375	16.2	38.9
APW16	06/16/2021	0.88	-123	7.4	1338	16.6	23.9
APW16	06/30/2021	0.88	-119	7.0	1331	16.8	7.06
APW16	07/15/2021	0.80	-143	7.4	1421	19.4	9.03
APW17	02/23/2021	2.55	-22.5	7.4	901.8	12.6	22.6

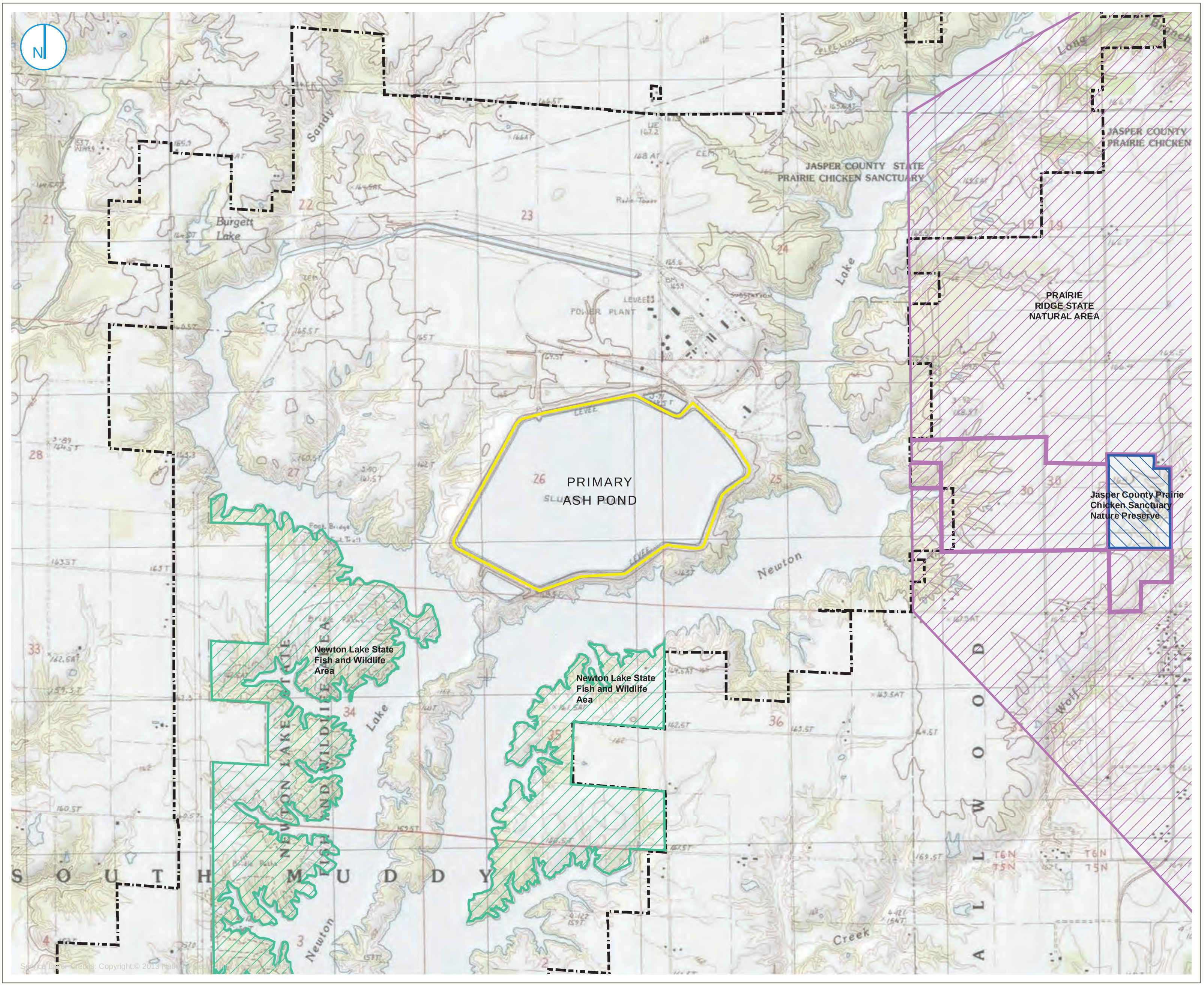
TABLE 4-2. GROUNDWATER FIELD PARAMETERS
HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, ILLINOIS

Sample Location	Sample Date	Dissolved Oxygen (mg/L)	Oxidation Reduction Potential (mV)	pH (field) (SU)	Specific Conductance (micromhos/cm)	Temperature (deg. C)	Turbidity (NTU)
APW17	03/10/2021	1.60	-132	7.7	951.8	13.8	0
APW17	03/30/2021	0.29	-87.2	7.1	1202	14.1	0
APW17	04/29/2021	3.40	-126	7.4	1042	16.3	9.5
APW17	05/24/2021	2.30	197	7.4	1206	20.8	29.5
APW17	06/16/2021	1.80	-130	7.4	1122	21.3	1.13
APW17	06/30/2021	1.30	-138	7.4	1206	19.7	3.13
APW17	07/15/2021	1.50	-110	7.4	1210	18.5	1.81
APW18	02/23/2021	1.94	-141	7.9	941.7	13.6	430
APW18	03/10/2021	0.80	-150	7.8	930.2	13.8	241
APW18	03/30/2021	0.49	-110	7.3	626.2	13.8	247
APW18	04/29/2021	1.50	-154	7.6	920	16.0	61.3
APW18	05/24/2021	2.30	120	7.6	1029	19.3	208
APW18	06/16/2021	0.75	-171	7.5	995	22.2	4.58
APW18	06/30/2021	0.41	-182	7.6	1011	21.6	8.28
APW18	07/15/2021	0.42	-154	7.6	1010	19.6	27.7

Notes:
Field readings are reported with as many significant figures as provided by analytical laboratory.
-- = data not available
cm = centimeter
deg. C = degrees Celsius
mg/L = milligrams per liter
mV = millivolts
NTU = nephelometric turbidity units
SU = standard units

generated 10/05/2021, 3:58:55 PM CDT

FIGURES



- ▭ PART 845 REGULATED UNIT FACILITY BOUNDARY
- ▨ JASPER COUNTY PRAIRIE CHICKEN SANCTUARY NATURE PRESERVE
- ▨ NEWTON LAKE STATE FISH AND WILDLIFE AREA
- ▨ PRAIRIE RIDGE STATE NATURAL AREA
- ⬚ PROPERTY BOUNDARY

0 1,000 2,000 Feet

SITE LOCATION MAP

HYDROGEOLOGIC SITE
CHARACTERIZATION REPORT
PRIMARY ASH POND
NEWTON POWER PLANT
NEWTON, ILLINOIS

FIGURE 1-1

RAMBOLL AMERICAS
ENGINEERING SOLUTIONS, INC.

RAMBOLL

R000768

PROJECT: 169000XXXX | DATED: 10/19/2021 | DESIGNER: STOLZSD

Y:\Mapping\Projects\22\2285\MXD\845_Operating_Permit\Newton\Figure 1-1_Site Location Map.mxd

Service Layer Credits: Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

🟨 PART 845 REGULATED UNIT FACILITY BOUNDARY
☐ SITE FEATURE
⬚ PROPERTY BOUNDARY

SITE MAP

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT PRIMARY ASH POND
NEWTON POWER PLANT
NEWTON, ILLINOIS

FIGURE 1-2

RAMBOLL AMERICAS
ENGINEERING SOLUTIONS, INC.

Service Layer Credits: Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

- 10-FOOT ELEVATION CONTOUR
- 2-FOOT ELEVATION CONTOUR
- 🟨 PART 845 REGULATED UNIT FACILITY BOUNDARY
- ☐ SITE FEATURE
- ⬚ PROPERTY BOUNDARY

NOTE
ELEVATION CONTOURS SHOWN IN FEET, NORTH AMERICAN VERTICAL DATUM OF 1988

SOURCE
INGENAE SURVEY, 2021

0 400 800 Feet

TOPOGRAPHIC MAP

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT PRIMARY ASH POND
NEWTON POWER PLANT
NEWTON, ILLINOIS

FIGURE 2-1

RAMBOLL AMERICAS
ENGINEERING SOLUTIONS, INC.

RAMBOLL

R000770

Y:\Mapping\Projects\22\2285\MXD\845_Operating_Permit\Newton\Figure 2-1_Topo Map.mxd

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PROJECT: 169000XXXX | DATED: 10/19/2021 | DESIGNER: STOLZSD

Y:\Mapping\Projects\22\2285\MXD\845_Operating_Permit\Newton\Figure 2-2_Soil Survey.mxd

- 🟨 PART 845 REGULATED UNIT FACILITY BOUNDARY
- ⬜ SITE FEATURE
- ⬜ NRCS SOIL SURVEY MAP UNIT BOUNDARY

MAP UNIT SYMBOL	MAP UNIT NAME
533	Urban land
866	Dumps, slurry
109A	Racoon silt loam, 0 to 2 percent
12A	Wynoose silt loam, 0 to 2 percent
13A	Bluford silt loam, 0 to 2 percent
13B2	Bluford silt loam, 2 to 5 percent slopes, eroded
14B	Ava silt loam, 2 to 5 percent slopes
14C2	Ava silt loam, 5 to 10 percent slopes, eroded
2A	Cisne silt loam, 0 to 2 percent
3333A	Wakeland silt loam, 0 to 2 percent slopes, frequently flooded
48A	Ebbert silt loam, 0 to 2 percent
581B2	Tamalco silt loam, 2 to 5 percent slopes, eroded
7C2	Atlas silt loam, 5 to 10 percent slopes, eroded
7C3	Atlas silty clay loam, 5 to 10 percent slopes, severely eroded
805C	Orthents, clayey, sloping
8F	Hickory silt loam, 18 to 35 percent
912A	Hoyleton-Darmstadt silt loams, 0 to 2 percent slopes
M-W	Miscellaneous water
W	Water

SOURCE:
NATURAL RESOURCES CONSERVATION SERVICE (NRCS)

0 400 800 Feet

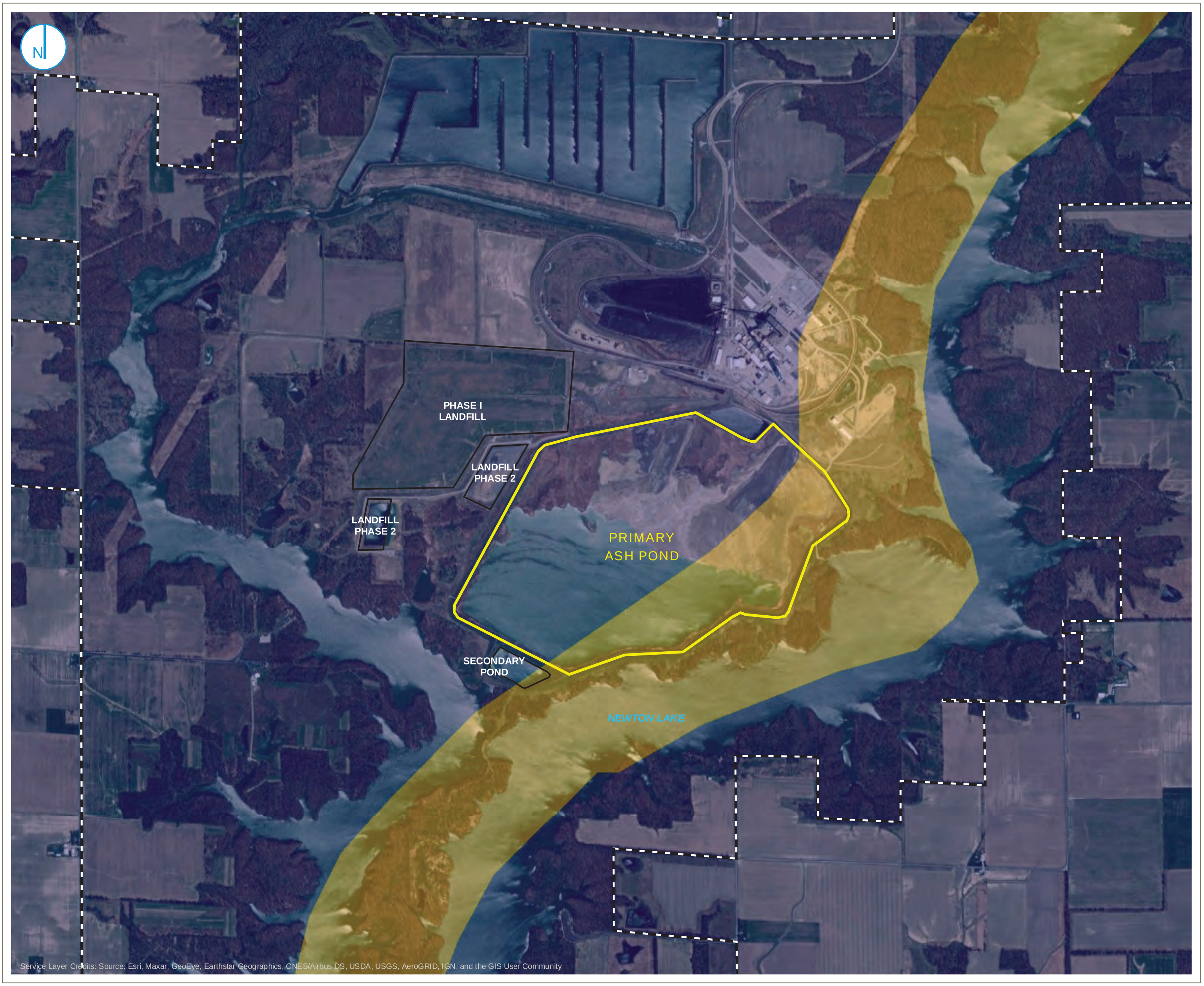
SOIL SURVEY MAP

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
PRIMARY ASH POND
NEWTON POWER PLANT
NEWTON, ILLINOIS

FIGURE 2-2

RAMBOLL AMERICAS ENGINEERING SOLUTIONS, INC.

RAMBOLL



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🟨 PART 845 REGULATED UNIT FACILITY BOUNDARY
☐ SITE FEATURE
🟧 CAHOKIA ALLUVIUM (INCLUDES ALLUVIAL FAN FACIES)
🟪 VANDALIA TILL MEMBER
⬚ PROPERTY BOUNDARY

SOURCE
ILLINOIS STATE GEOLOGICAL SURVEY (ISGS)

0 750 1,500 Feet

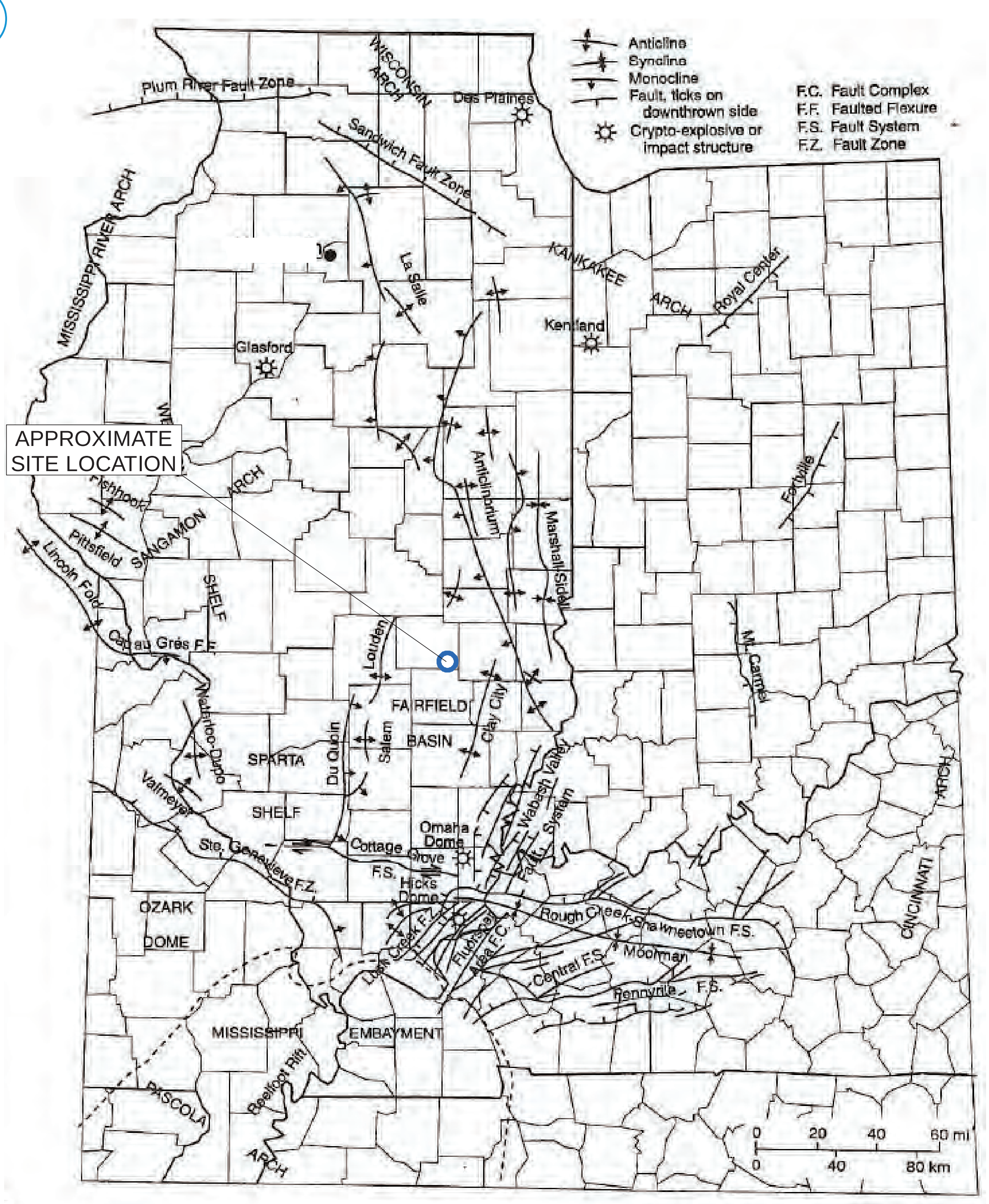
SURFICIAL GEOLOGIC DEPOSITS

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
PRIMARY ASH POND
NEWTON POWER PLANT
NEWTON, ILLINOIS

FIGURE 2-3

RAMBOLL AMERICAS
ENGINEERING SOLUTIONS, INC.

RAMBOLL



SOURCE NOTE: MODIFIED FROM "NELSON, W.J. 1995, STRUCTURAL FEATURES IN ILLINOIS, ILLINOIS STATE GEOLOGICAL SURVEY, BULLETIN 100, CHAMPAIGN, ILLINOIS."

Service Layer Credits:

Y:\Mapping\Projects\22\2285\MXD\845_Operating_Permit\Newton\Figure 2-4_Major Structural Features of Illinois.mxd

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MAJOR STRUCTURAL FEATURES OF ILLINOIS

PRIVILEGED AND CONFIDENTIAL
PREPARED AT THE REQUEST OF COUNSEL

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
PRIMARY ASH POND
NEWTON POWER PLANT
NEWTON, ILLINOIS

DRAFT

FIGURE 2-4

RAMBOLL AMERICAS
ENGINEERING SOLUTIONS, INC.

Service Layer Credits: Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

▣	MONITORING WELL
▣	SOURCE SAMPLE LOCATION
◒	STAFF GAGE
⊕	SOIL BORING
🟨	PART 845 REGULATED UNIT FACILITY BOUNDARY
☐	SITE FEATURE

0 400 800 Feet

FIELD INVESTIGATION LOCATIONS

HYDROGEOLOGIC SITE
CHARACTERIZATION REPORT
PRIMARY ASH POND
NEWTON POWER PLANT
NEWTON, ILLINOIS

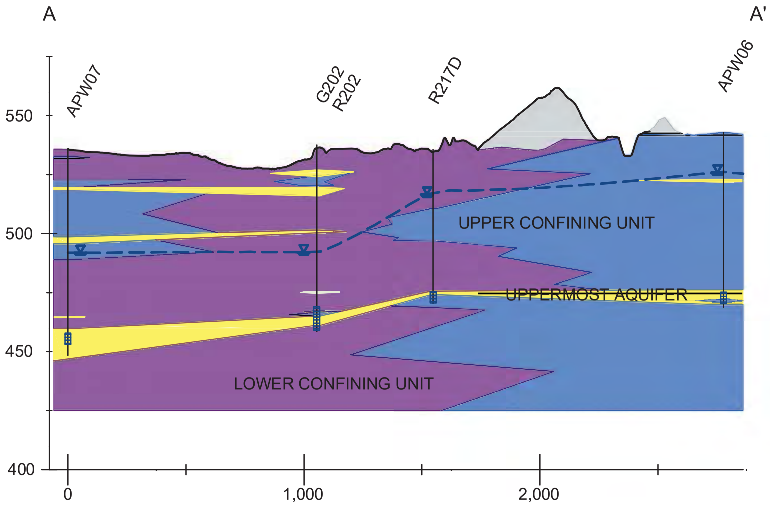
FIGURE 2-5

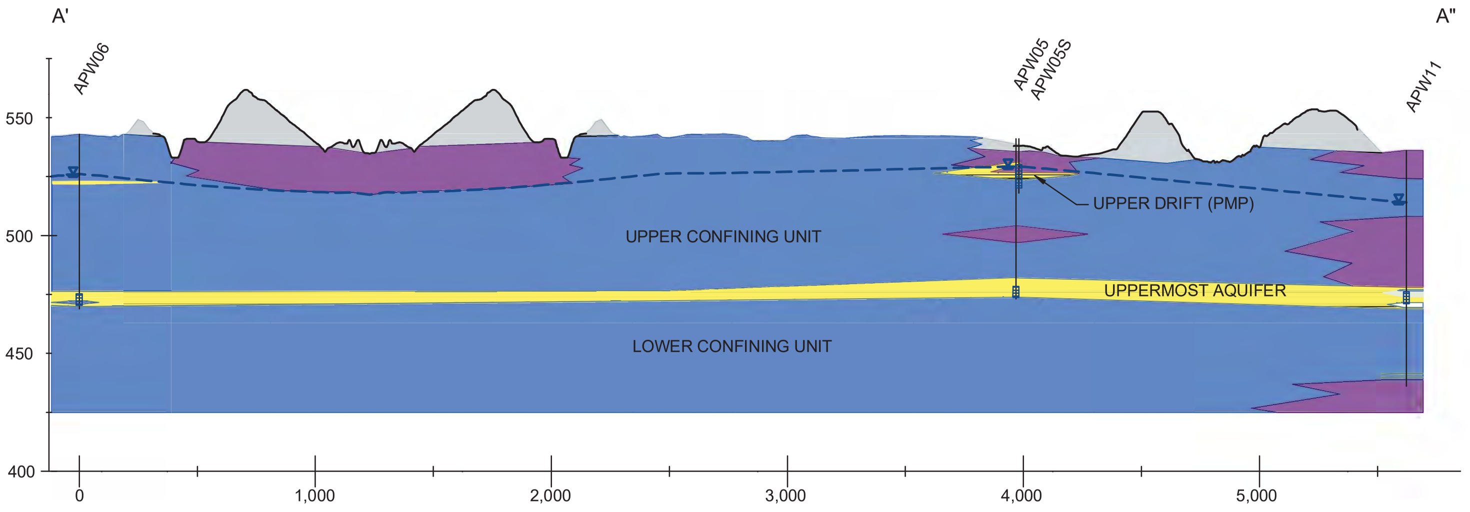
RAMBOLL AMERICAS
ENGINEERING SOLUTIONS, INC.

RAMBOLL

Y:\Mapping\Projects\22\2285\MXD\845_Operating_Permit\Newton\Figure 2-5_Field Investigation Locations.mxd

PROJECT: 169000XXXX | DATED: 10/19/2021 | DESIGNER: STOLZSD



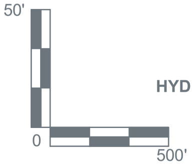


NOTES

1. This profile was developed by interpolation between widely spaced boreholes. Only at the borehole location should it be considered as an approximately accurate representation and then only to the degree implied by the notes on the borehole logs.
2. Scale is approximate.
3. Vertical scale is exaggerated 10X.
4. Groundwater elevations measured on June 24, 2021.
5. PMP = potential migration pathway

LEGEND

▨	FILL
▨	CLAY (CL/CH)
▨	SILT (ML)
▨	SAND (SP/SM/SW)
▨	GRAVEL (GP/GW)
▤	WELL SCREEN INTERVAL
~	UPPERMOST AQUIFER POTENTIOMETRIC SURFACE
▽	UPPERMOST AQUIFER GROUNDWATER ELEVATION



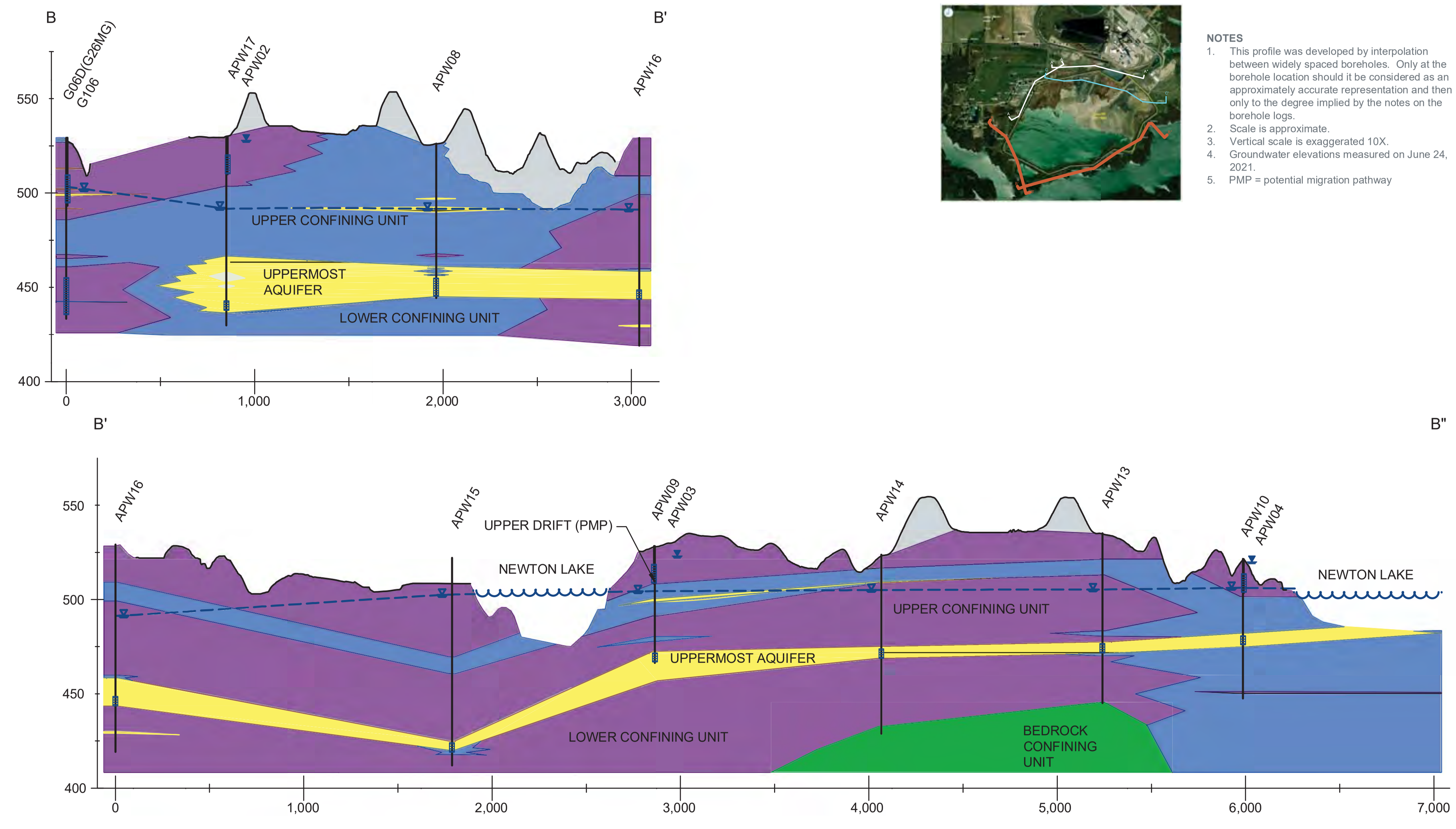
GEOLOGIC CROSS SECTION
A-A' & A'-A"

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
PRIMARY ASH POND
NEWTON POWER PLANT
NEWTON, ILLINOIS

FIGURE 2-6

RAMBOLL AMERICAS
ENGINEERING SOLUTIONS, INC.

PROJECT: ####
\\ramboll.sharepoint.com@SSL\DavWWWRoot\sites\vistra\Shared Documents\-CCR GW\Deliverables\Part 845 Operating Permits\Sites\Newton\Hydrogeo\EVS\working files\CAD\Cross Sections\Newton-Cross Sections.dwg
DATED: 10/8/2021
DESIGNER: ENGELHSA



NOTES
1. This profile was developed by interpolation between widely spaced boreholes. Only at the borehole location should it be considered as an approximately accurate representation and then only to the degree implied by the notes on the borehole logs.
2. Scale is approximate.
3. Vertical scale is exaggerated 10X.
4. Groundwater elevations measured on June 24, 2021.
5. PMP = potential migration pathway

LEGEND

▭	FILL
🟪	CLAY (CL/CH)
🟦	SILT (ML)
🟨	SAND (SP/SM/SW)
▭	GRAVEL (GP/GW)
🟩	BEDROCK / WEATHERED BEDROCK (SHALE)
▤	WELL SCREEN INTERVAL
~	UPPERMOST AQUIFER POTENTIOMETRIC SURFACE
▼	UPPERMOST AQUIFER GROUNDWATER ELEVATION
▼	BEDROCK GROUNDWATER / OTHER GROUNDWATER / SURFACE WATER ELEVATION(S)

50'
0
500'

GEOLOGIC CROSS SECTION
B-B' & B'-B''

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
PRIMARY ASH POND
NEWTON POWER PLANT
NEWTON, ILLINOIS

FIGURE 2-7

RAMBOLL AMERICAS
ENGINEERING SOLUTIONS, INC.

RAMBOLL

PROJECT: ####
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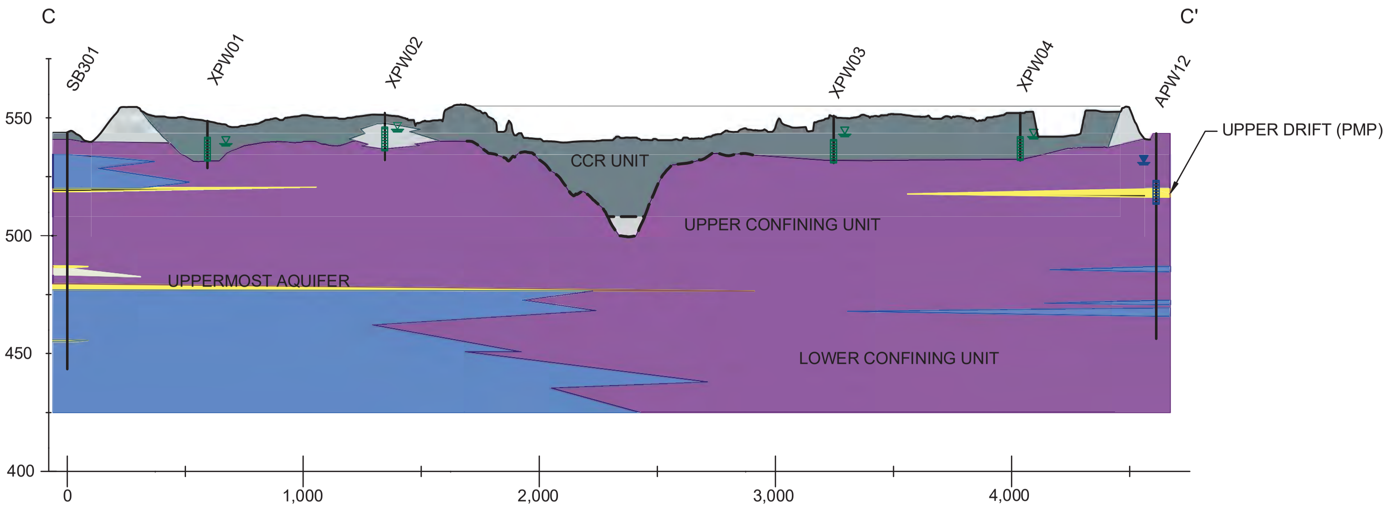
DATED: 10/8/2021 DESIGNER: ENGELHSA

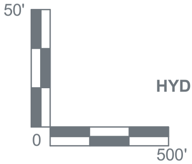
NOTES
1. This profile was developed by interpolation between widely spaced boreholes. Only at the borehole location should it be considered as an approximately accurate representation and then only to the degree implied by the notes on the borehole logs.
2. Scale is approximate.
3. Vertical scale is exaggerated 10X.
4. Base of CCR Unit is based on historic land surface contours. This surface is being further evaluated as the construction permit is being developed.
5. Groundwater elevations measured on June 24, 2021.
6. PMP = potential migration pathway



LEGEND

■ COAL COMBUSTION RESIDUALS (CCR)
■ FILL
■ CLAY (CL/CH)
■ SILT (ML)
■ SAND (SP/SM/SW)
■ GRAVEL (GP/GW)

▤ WELL SCREEN INTERVAL
▽ POREWATER ELEVATION
▼ BEDROCK GROUNDWATER / OTHER GROUNDWATER / SURFACE WATER ELEVATION(S)



GEOLOGIC CROSS SECTION
C-C'

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
PRIMARY ASH POND
NEWTON POWER PLANT
NEWTON, ILLINOIS

FIGURE 2-8

RAMBOLL AMERICAS
ENGINEERING SOLUTIONS, INC.

PROJECT: ####
DATED: 10/8/2021 DESIGNER: ENGELHSA
\\ramboll.sharepoint.com@SSL\DavWWWRoot\sites\vista\Shared Documents\-CCR GW\Deliverables\Part 845 Operating Permits\Sites\Newton\Hydrogeo\EVS\working files\CAD\Cross Sections\Newton-Cross Sections.dwg

Service Layer Credits: Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

- ⯐ SOIL BORING AND BOTTOM OF ASH ELEVATION
- — 10 FOOT HISTORIC ELEVATION CONTOUR
- — 2 FOOT HISTORIC ELEVATION CONTOUR
- ▭ CONSTRUCTION DRAWING S-69 INDICATES DRAINAGE FEATURE WAS TO BE FILLED TO MAX ELEVATION 508 PRIOR TO OPERATION OF THE UNIT.
- ▭ PART 845 REGULATED UNIT FACILITY BOUNDARY
- ▭ SITE FEATURE
- ⬚ PROPERTY BOUNDARY

NOTES

1. CONTOUR LINES ARE A HISTORIC LAND SURFACE. THIS SURFACE IS BEING FURTHER EVALUATED AS THE CONSTRUCTION PERMIT IS BEING DEVELOPED.

0 400 800 Feet

BOTTOM OF ASH MAP

HYDROGEOLOGIC SITE
CHARACTERIZATION REPORT
PRIMARY ASH POND
NEWTON POWER PLANT
NEWTON, ILLINOIS

FIGURE 2-9

RAMBOLL AMERICAS
ENGINEERING SOLUTIONS, INC.

RAMBOLL

R000778

Y:\Mapping\Projects\22\2285\MXD\845_Operating_Permit\Newton\Figure 2-9_Bottom of Ash Map.mxd

PROJECT: 169000XXXX | DATED: 10/19/2021 | DESIGNER: STOLZSD

Service Layer Credits: Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Y:\Mapping\Projects\22\2285\MXD\845_Operating_Permit\Newton\Figure 3-1_Monitoring Well Location Map.mxd

PROJECT: 169000XXXX | DATED: 10/19/2021 | DESIGNER: STOLZSD

- ▨ BACKGROUND WELL
- ▨ MONITORING WELL
- ▨ SOURCE SAMPLE LOCATION
- ◒ STAFF GAGE
- ▭ PART 845 REGULATED UNIT FACILITY BOUNDARY
- ▭ SITE FEATURE

0 400 800 Feet

MONITORING WELL LOCATIONS

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
PRIMARY ASH POND
NEWTON POWER PLANT
NEWTON, ILLINOIS

FIGURE 3-1

RAMBOLL AMERICAS
ENGINEERING SOLUTIONS, INC.

RAMBOLL

Service Layer Credits: Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

- ▪ MONITORING WELL
- ― UPPERMOST AQUIFER ELEVATION (2-FOOT INTERVAL)
- ▭ PART 845 REGULATED UNIT FACILITY BOUNDARY
- ▭ SITE FEATURE
- ⬚ PROPERTY BOUNDARY

NOTES:
* = NOT USED FOR CONTOURING
ELEVATION CONTOURS SHOWN IN FEET, NORTH AMERICAN VERTICAL DATUM OF 1988 (NAVD88)

TOP OF AQUIFER CONTOURS GENERATED IN 2018 (HALEY & ALDRICH, INC., 2018) FOR 40 C.F.R. § 257; CONTOURS HAVE NOT BEEN MODIFIED USING BORING DATA COLLECTED IN 2021, ALTHOUGH THE SEPARATION DISTANCE BETWEEN THE TOP OF UPPERMOST AQUIFER AND BOTTOM OF ASH IS CONSISTENT.

0 400 800 Feet

TOP OF UPPERMOST AQUIFER

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
PRIMARY ASH POND
NEWTON POWER PLANT
NEWTON, ILLINOIS

FIGURE 3-2

RAMBOLL AMERICAS
ENGINEERING SOLUTIONS, INC.

PROJECT: 169000XXXX | DATED: 10/19/2021 | DESIGNER: STOLZSD

Y:\Mapping\Projects\22\2285\MXD\845_Operating_Permit\Newton\Figure 3-2_Top of Uppermost Aquifer.mxd

Service Layer Credits: Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

- ▨ BACKGROUND WELL
- ▨ MONITORING WELL
- ▨ SOURCE SAMPLE LOCATION
- ◒ STAFF GAGE
- — GROUNDWATER ELEVATION CONTOUR (5-FT CONTOUR INTERVAL, NAVD88)
- - - INFERRED GROUNDWATER ELEVATION CONTOUR
- → GROUNDWATER FLOW DIRECTION
- ☐ PART 845 REGULATED UNIT (SUBJECT UNIT)
- ☐ SITE FEATURE

NOTES:

1. ELEVATIONS IN PARENTHESES WERE NOT USED FOR CONTOURING.
2. NM = NOT MEASURED
3. ELEVATION CONTOURS SHOWN IN FEET, NORTH AMERICAN VERTICAL DATUM OF 1988

0 400 800 Feet

UPPERMOST AQUIFER GROUNDWATER ELEVATION CONTOURS APRIL 27, 2021

HYDROGEOLOGIC SITE
CHARACTERIZATION REPORT
PRIMARY ASH POND
NEWTON POWER PLANT
NEWTON, ILLINOIS

FIGURE 3-3

RAMBOLL AMERICAS
ENGINEERING SOLUTIONS, INC.

RAMBOLL

R000781

PROJECT: 169000XXXX | DATED: 10/19/2021 | DESIGNER: STOLZSD

Y:\Mapping\Projects\22\2285\MXD\845_Operating_Permit\Newton\Figure 3-3_GWE_Contours_20210427.mxd

Service Layer Credits: Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

- ▨ BACKGROUND WELL
- ▨ MONITORING WELL
- ▨ SOURCE SAMPLE LOCATION
- ◐ STAFF GAGE
- — GROUNDWATER ELEVATION CONTOUR (5-FT CONTOUR INTERVAL, NAVD88)
- - - INFERRED GROUNDWATER ELEVATION CONTOUR
- → GROUNDWATER FLOW DIRECTION
- ☐ PART 845 REGULATED UNIT (SUBJECT UNIT)
- ☐ SITE FEATURE

NOTES:

1.ELEVATIONS IN PARENTHESIS WERE NOT USED FOR CONTOURING.

2. NM = NOT MEASURED

3. ELEVATION CONTOURS SHOWN IN FEET, NORTH AMERICAN VERTICAL DATUM OF 1988

0 400 800 Feet

UPPERMOST AQUIFER GROUNDWATER ELEVATION CONTOURS
JULY 14, 2021

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
PRIMARY ASH POND
NEWTON POWER PLANT
NEWTON, ILLINOIS

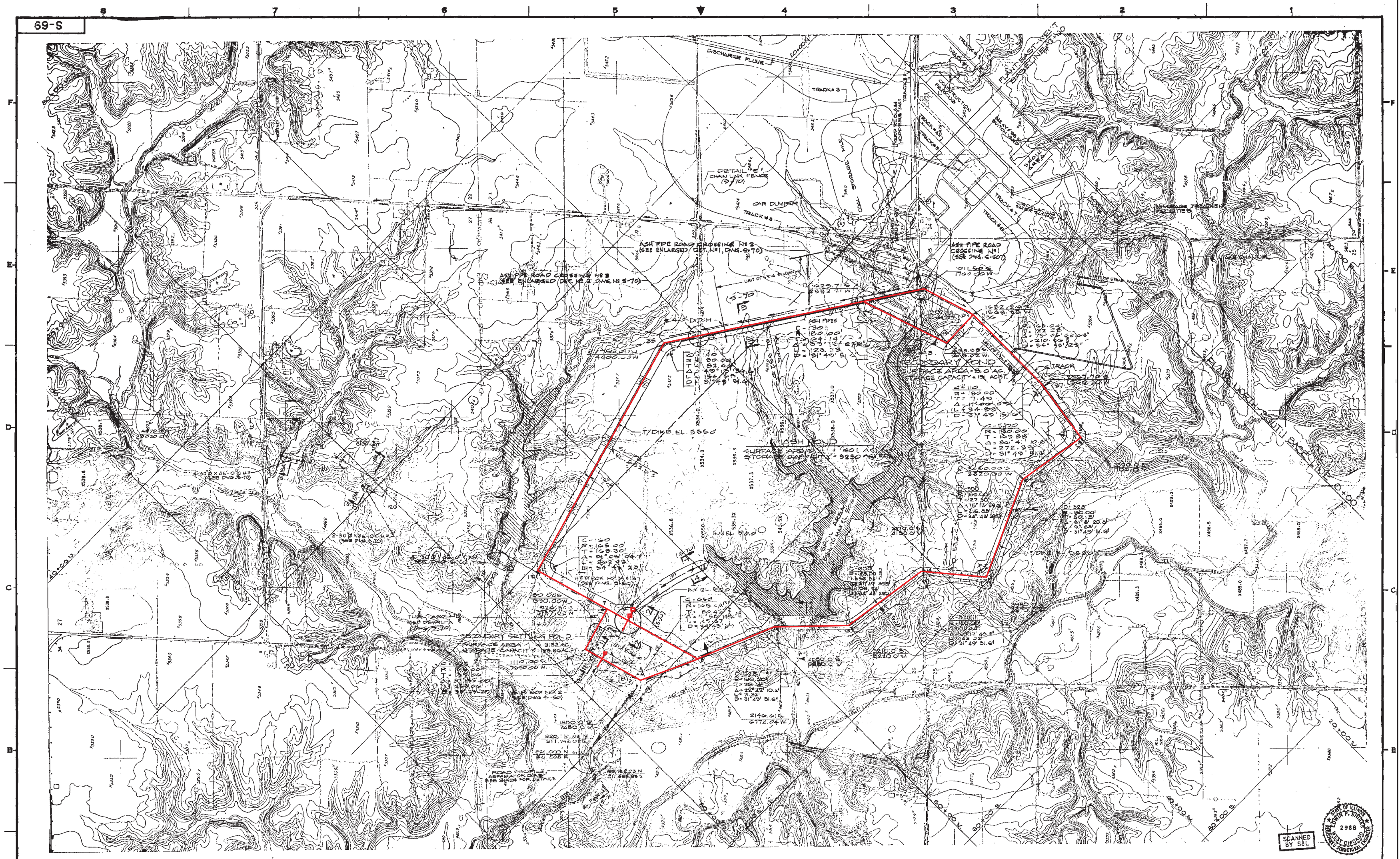
FIGURE 3-4

RAMBOLL AMERICAS
ENGINEERING SOLUTIONS, INC.

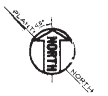
RAMBOLL

APPENDICES

APPENDIX A
HISTORIC TOPOGRAPHIC MAP S-69



2988



POINT NO.	SIDE	CURVE NO.	R	T	Δ	L	D
8	ASH POND		100'	52.87'	49°43' 13.6"	86.78	57°17' 45.00"
8	SECONDARY ASH POND		65'	140.79'	130°16' 46.4"	147.80	88°08' 51.69"
21	LAKESIDE (A)		165'	49.55	33°25' 06.4"	96.27	34°43' 29.00"
21	LAKESIDE (B)		65'	70.49'	94°36' 00.0"	107.32	88°08' 51.69"
36	ASH POND (A)		57.5'	57.50	90°00' 00.0"	90.27	99°38' 41.53"
36	SECONDARY (B) POND		57.5	77.59	106°54' 52.38"	107.24	99°38' 41.53"
37	SECONDARY POND		57.5	161.37	140°46' 29.17"	141.21	99°58' 41.53"

NOTES

7. THE WATER LEVEL IN ASH POND SHALL BE MAINTAINED AT AN ELEVATION 10'-0" ABOVE THE SEDIMENT LEVEL FOR ENVIRONMENTAL PURPOSES.

NOTES

1. FOR GENERAL NOTES SEE DWG. S-14.
2. ALL WORK SHOWN IN THIS DRAWING SHALL BE DONE BY SUPERSTRUCTURE CONTRACTOR IN ACCORDANCE WITH JOB SPEC. A-3022.
3. ALL EXTERIOR SIDE SLOPES OF DIKE BELOW ELEV. 510.0' THAT IS TO BE CONSTRUCTED BEFORE LAKE FILLING, SHALL BE PROVIDED WITH 24" STONE RIPRAP ON 24" SAND AND GRAVEL FILTER BEDDING AS SHOWN ON DWG. S-70, AND ALL DIKE CONSTRUCTION SHALL BE DONE IN ACCORDANCE WITH JOB SPEC. A-3017 AND A-3022.
4. ALL DIKE TOPS AND SIDE SLOPES AND ALL EXTERNAL DITCHES SHALL BE PROVIDED WITH 4" TOPSOIL AND SEEDED IN ACCORDANCE WITH JOB SPEC. A-3017 AND A-3022.
5. EXISTING LOW AREAS SHALL BE FILLED WITH SPOILMATERIAL AS REQUIRED FOR SPOIL DISPOSAL SPOILS SHALL BE PLACED IN LAYERS AND GRADED PROPERLY FOR DRAINAGE.
6. REMOVED "HOLD" FROM SO_2 POND AREAS FOR CLEARING, SLOPE STAKING & CROSS-SECTIONING ONLY.

REFERENCE DRAWINGS

S-19	SITE CONTOURS AND DEVELOPMENT PLAN SHEET 4.
S-39	GRADING AND DRAINAGE PLAN, PLANT AREA SHEET 2.
S-40	GRADING AND DRAINAGE PLAN, PLANT AREA SHEET 3.
S-50	WEIR BOX STRUCTURES AT PRIMARY AND SECONDARY SETTLING PONDS.
S-70	ASH POND DIKE PROFILE DETAILS & SECTION
S-507	GRADING & DRAINAGE PLAN- PLANT AREA- SHT7.

Drawing Release Record

Rev.	Date	Init.	Description
N	07-29-94	TM	SCANNED BY S&L
A	11-29-74	CRB	[illegible]
B	2-10-75		REMOVED SO_2 [illegible]
C			HOLD [illegible]
D	7-15-75	CRB	[illegible]
E	12-24-75	CRB	REMOVED HOLD [illegible]
F	7-12-76	CRB	[illegible]
G	9-13-76	CRB	[illegible]
	—	—	WEIR BOX [illegible]
	—	—	[illegible]
H	1-24-77	CRB	[illegible]
J	10-21-77	SPL	[illegible]
K	1-8-79	ENA	[illegible]
L	7-8-80	[illegible]	[illegible]
[illegible]	2-20-[illegible]	[illegible]	SENT TO CLIENT

ASH POND & SO_2
DISPCSAL POND
NEWTON POWER STATION UNIT 1
CENTRAL ILL PUBLIC SERVICE CO.
NEWTON, ILLINOIS

SCALE 1" = 400'-0" & U.O.
DRAWN B. SANCHEZ 8-6-74
CHECKED C. R. Bhattacharya 8-6-74
ENGINEER A. J. Shah 8-6-74
APPROVED [illegible]
JOB NO. 4136-58 4136-15

SARGENT & LUNDY
ENGINEERS
CHICAGO

DRAWING NO.
S-69

APPENDIX B
INFORMATION PERTINENT TO 35 I.A.C. § 845.220(A)(3)

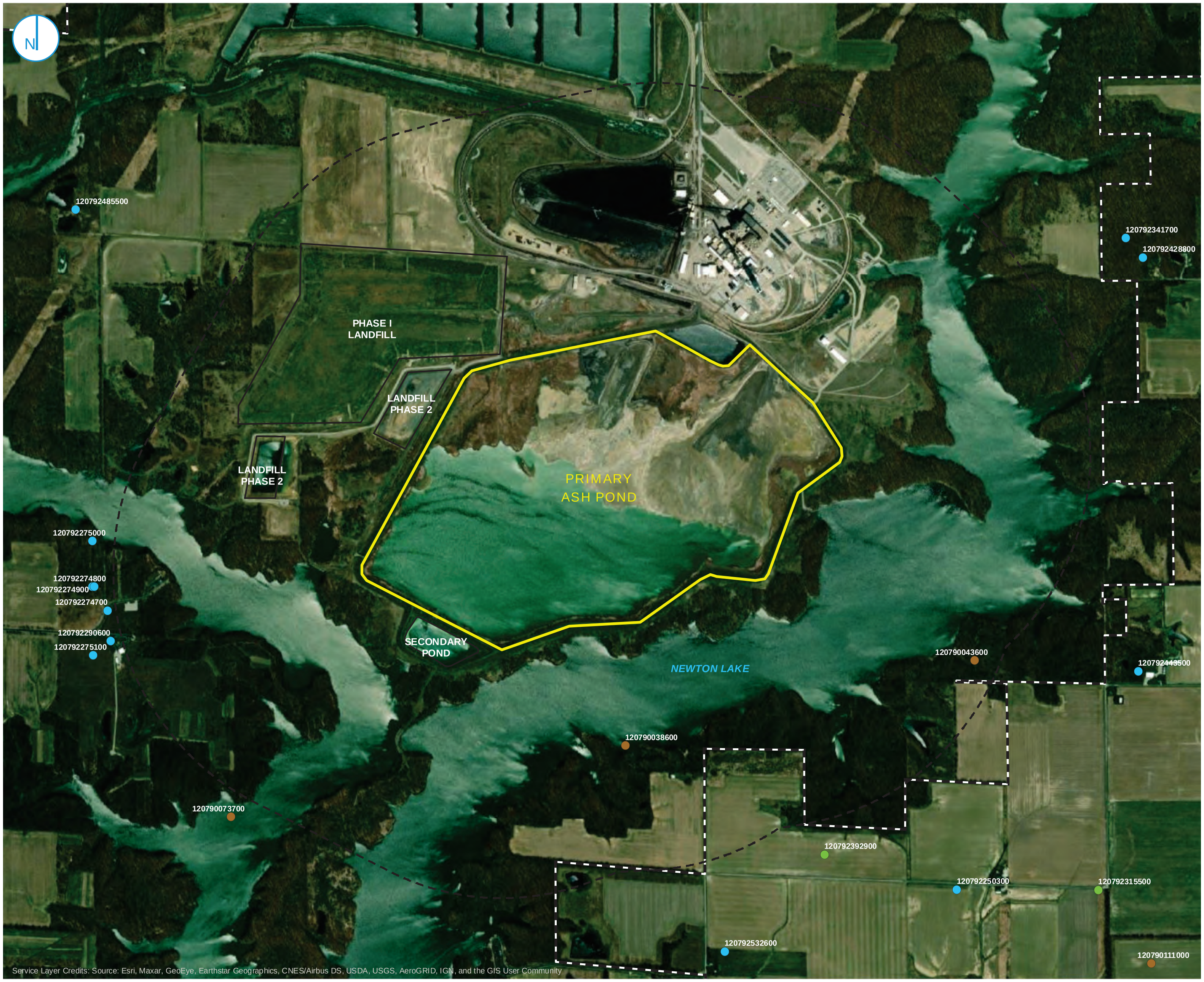
SUMMARY OF POTENTIAL RECEPTORS WITHIN 1,000 METERS

DESKTOP STUDY
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

Category	Number of Receptors Identified Within 1,000 Meters	Number of Receptors Identified Downgradient of Unit	Notes
Wells	2	0	Sidegradient; Wells are listed as dry/abandoned.
Surface Water Features	12	2	
Historic Sites	0	0	
Natural Sites	0	0	
Threatened or Endangered Species	25	10	Data provided only at a county level.
Mines	0	0	Nearest mine is 6.7 miles northeast.
Oil Sites	0	0	

[O: CJC 06/02/21; C: LDC 09/15/21]

WATER WELL SURVEY



Service Layer Credits: Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

● DRY
● WATER
● N/A
▭ PART 845 REGULATED UNIT FACILITY BOUNDARY
⬚ 1000 METER UNIT BUFFER
▭ SITE FEATURE
⬚ PROPERTY BOUNDARY

SOURCE: IL WELLS

0 625 1,250 Feet

DRINKING WATER INTAKES, PUMPING WELLS, AND USES OF WATER

HYDROGEOLOGIC SITE CHARACTERIZATION REPORT
PRIMARY ASH POND
NEWTON POWER PLANT
NEWTON, ILLINOIS

FIGURE B-1

RAMBOLL AMERICAS
ENGINEERING SOLUTIONS, INC.

RAMBOLL

PROJECT: 169000XXXX | DATED: 10/19/2021 | DESIGNER: STOLZSD

Y:\Mapping\Projects\22\2285\MXD\845_Operating_Permit\Newton\Figure B-2_Drinking Water Intakes Uses of Water.mxd

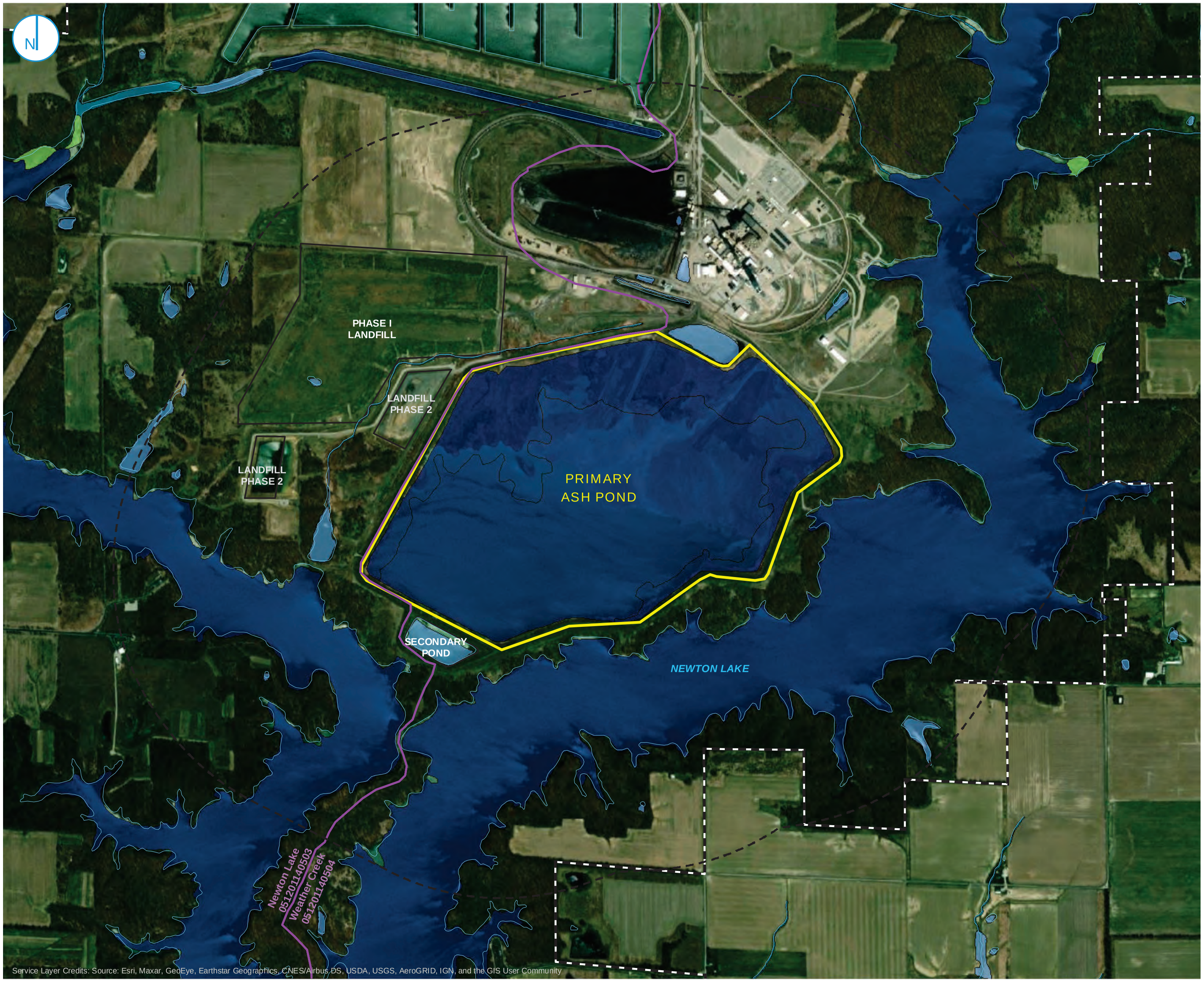
WELLS WITHIN 1,000 METERS
DESKTOP STUDY
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

Well Number	Date Constructed	Ground Elevation (ft NAVD88)	Screen Top Depth (FT BGS)	Screen Bottom Depth (ft BGS)	Screen Length (ft)	Screen Diameter (inches)	Well Depth (ft BGS)	Total Boring Depth (ft BGS)	Latitude (DD)	Longitude (DD)	Hydraulic Position Designation (B/Sd/U/D)	Notes
120790038600	5/27/1948	---	---	---	---	---	---	---	38.918277	-88.281956	Sd	
120790043600	7/13/1950	---	---	---	---	---	---	---	38.921356	-88.265738	Sd	

[O: CJC 06/02/21; C: LDC 09/15/21]

Notes:
--- = no data
B = background
BGS = below ground surface
D = downgradient
DD = decimal degrees
ft = foot/feet
LCU = lower confining unit
Sd= Sidegradient
U = upgradient
NAVD88 = North American Vertical Datum of 1988, GEOID 12A

SURFACE WATERS



Service Layer Credits: Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

- SURFACE WATERBODY
- ▭ WATERSHED BOUNDARY (HUC 12)

NATIONAL WETLANDS INVENTORY

- ● FRESHWATER EMERGENT WETLAND
- ● FRESHWATER FORESTED/SHRUB WETLAND
- ● FRESHWATER POND
- ● LAKE
- ● OTHER
- ● RIVERINE
- ▭ PART 845 REGULATED UNIT FACILITY BOUNDARY
- ⬚ 1000 METER UNIT BUFFER
- ▭ SITE FEATURE
- ⬚ PROPERTY BOUNDARY

SOURCES: USGS, USFWS

0 625 1,250 Feet

SURFACE WATERBODIES

HYDROGEOLOGIC SITE
CHARACTERIZATION REPORT
PRIMARY ASH POND
NEWTON POWER PLANT
NEWTON, ILLINOIS

FIGURE B-2

RAMBOLL AMERICAS
ENGINEERING SOLUTIONS, INC.

RAMBOLL

Y:\Mapping\Projects\22\2285\MXD\845_Operating_Permit\Newton\Figure B-3_Surface Waterbodies.mxd

PROJECT: 169000XXXX | DATED: 10/19/2021 | DESIGNER: STOLZSD

SURFACE WATER FEATURES WITHIN 1,000 METERS

DESKTOP STUDY
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

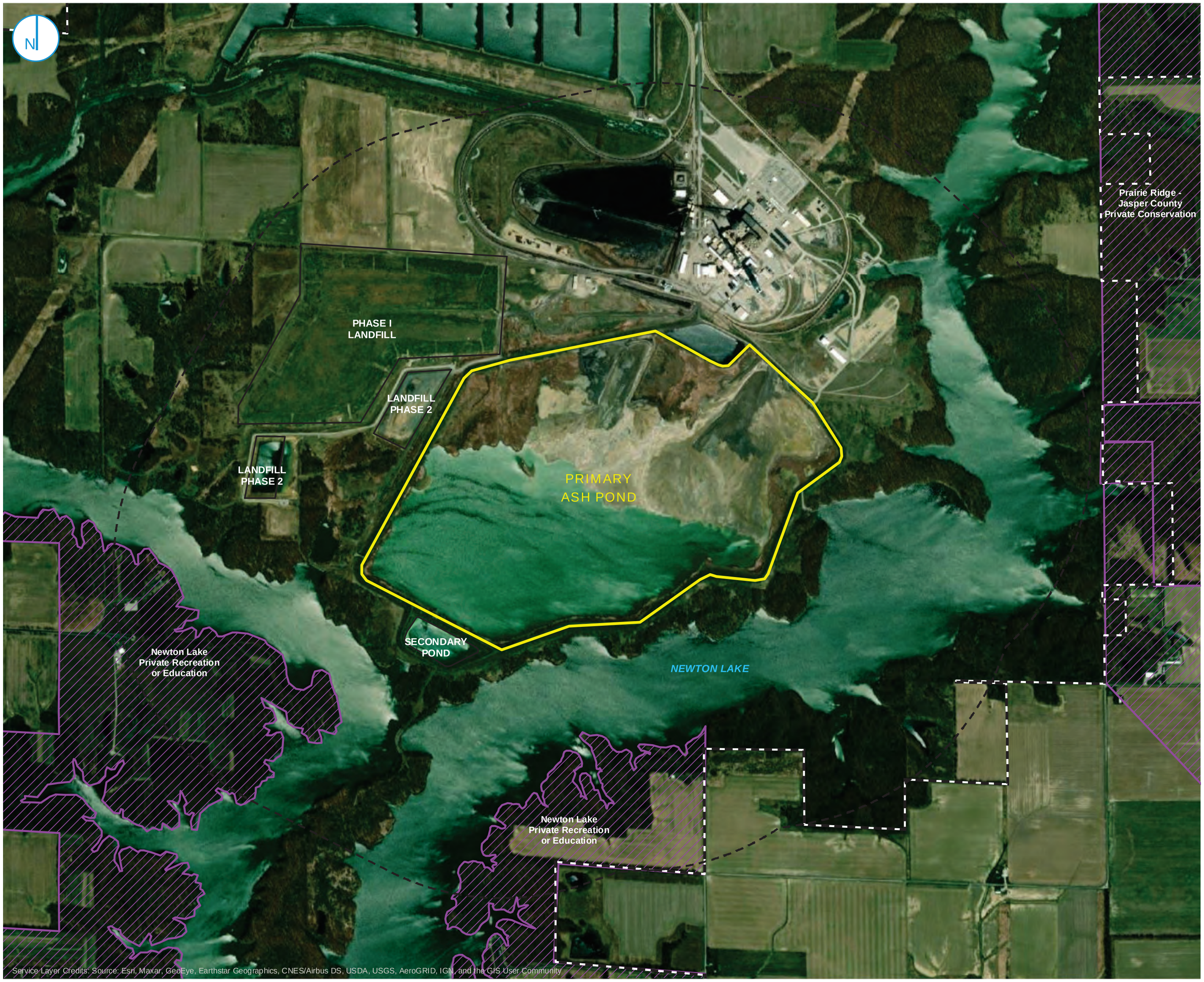
HUC	Surface Water ID	Distance from Unit (ft)	Distance from Unit (meters)	Physical Orientation to Unit	Hydraulic Orientation to Unit	Classification Code	Size (acres)
--	Freshwater Pond	45	14	NE	Upgradient	PUBGh	6.16
--	Freshwater Pond	2610	795	SE	Sidegradient	PUBGh	2.28
--	Freshwater Pond	3250	991	NW	Upgradient	PUBGh	4.07
--	Freshwater Pond 2	153	47	SW	Downgradient	PUBGh	5.79
--	Freshwater Pond 3	958	292	NE	Upgradient	PUBGh	0.92
--	Freshwater Pond 4	720	219	N	Upgradient	PUBGx	0.99
--	Freshwater Pond 5	440	134	W	Upgradient	PUBGh	3.7
--	Freshwater Pond 6	1600	488	NW	Upgradient	PUBGh	0.27
--	Lake	2780	847	N	Upgradient	L1UBHx	13.72
--	Lake Newton	240	73	S	Downgradient	L1UBHh	1647.98
--	Riverine Wetland	123	37	N	Upgradient	R4SBC	2.26
--	Riverine Wetland 2	142	43	N/NW	Upgradient	R4SBC	2.26

[O: CJC 06/02/21; C: LDC 09/15/21]

Notes:

-- = not applicable
ft = foot/feet
bgs = below ground surface
HUC = Hydrologic Unit Code
N = north
W = west
SE = southeast

NATURE PRESERVES, HISTORIC SITES, ENDANGERED/THREATENED SPECIES



Service Layer Credits: Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

▨ PROTECTED
☐ PART 845 REGULATED UNIT FACILITY BOUNDARY
⬚ 1000 METER UNIT BUFFER
☐ SITE FEATURE
⬚ PROPERTY BOUNDARY

SOURCES: USGS - PAD-US, USFWS

0 625 1,250 Feet

NATURE PRESERVES

HYDROGEOLOGIC SITE
CHARACTERIZATION REPORT
PRIMARY ASH POND
NEWTON POWER PLANT
NEWTON, ILLINOIS

FIGURE B-3

RAMBOLL AMERICAS
ENGINEERING SOLUTIONS, INC.

RAMBOLL

Y:\Mapping\Projects\22\2285\MXD\845_Operating_Permit\Newton\Figure B-4_Nature Preserves.mxd

PROJECT: 169000XXXX | DATED: 10/19/2021 | DESIGNER: STOLZSD

JASPER COUNTY THREATENED AND ENDANGERED SPECIES

DESKTOP STUDY
NEWTON POWER PLANT
PRIMARY ASH POND
NEWTON, IL

Scientific Name	Common Name	Status	Number of Occurances	Last Observed
Ammocrypta pellucida	Eastern Sand Darter	LT	9	8/5/2019
Apalone mutica	Smooth Softshell	LT	2	8/31/2017
Asio flammeus	Short-eared Owl	LE	2	12/23/2014
Bartramia longicauda	Upland Sandpiper	LE	1	5/22/2013
Botaurus lentiginosus	American Bittern	LE	1	6/3/2013
Circus hudsonius	Northern Harrier	LE	3	2/6/2016
Coccyzus erythropthalmus	Black-billed Cuckoo	LT	1	6/25/1998
Emydoidea blandingii	Blanding's Turtle	LE	1	5/18/1998
Etheostoma histrio	Harlequin Darter	LE	1	9/18/1967
Festuca paradoxa	Cluster Fescue	LT	1	6/30/1999
Ixobrychus exilis	Least Bittern	LT	2	5/26/2017
Lanius ludovicianus	Loggerhead Shrike	LE	3	6/7/2017
Laterallus jamaicensis	Black Rail	LE	1	6/20/2012
Nyctanassa violacea	Yellow-crowned Night-Heron	LE	1	5/24/1995
Papaipema eryngii	Eryngium Stem Borer	LT	1	7/8/2020
Penstemon tubaeflorus	Tube Beard Tongue	LE	3	5/27/2019
Rallus elegans	King Rail	LE	1	6/7/2016
Sabatia campestris	Prairie Rose Gentian	LE	1	7/30/2019
Schoenoplectus purshianus	Pursh's Bulrush	LE	1	2012
Silene regia	Royal Catchfly	LE	1	5/12/2015
Spiranthes vernalis	Spring Ladies' Tresses	LE	3	8/5/2019
Sternula antillarum	Least Tern	LE	1	6/13/2004
Terrapene ornata	Ornate Box Turtle	LT	2	4/6/2020
Tracaulon arifolium	Halberd-leaved Tearthumb	LE	1	8/14/1985
Tympanuchus cupido	Greater Prairie-Chicken	LE	2	7/10/1905

[O: CJC 06/02/21; C: LDC 09/15/21]

Notes:
-- = not provided/cannot be determined
LE = listed endangered
LT = listed threatened

APPENDIX C
BORING LOGS AND WELL CONSTRUCTION LOGS

BORING AND WELL LOCATION MAP

BORING LOGS

SOIL BORING LOG INFORMATION

Page 1 of 6

Facility/Project Name Newton Power Station	License/Permit/Monitoring Number	Boring Number APW11

Boring Drilled By: Name of crew chief (first, last) and Firm Dave Gordon Cascade Drilling	Date Drilling Started 1/23/2021	Date Drilling Completed 1/23/2021	Drilling Method Mini Sonic
Common Well Name APW11	Final Static Water Level Feet (NAVD88)	Surface Elevation 536.05 Feet (NAVD88)	Borehole Diameter 6.0 inches

Local Grid Origin ☐ (estimated: ☐) or Boring Location ☒

State Plane 825,195.28 N, 1,000,717.50 E [✓ E]/ W

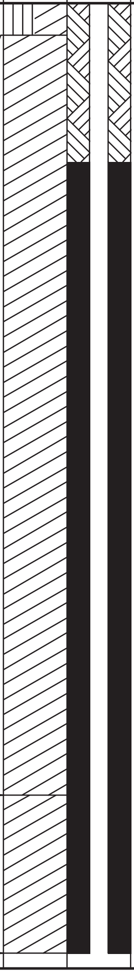
1/4 of 1/4 of Section 25, T 6 N, R 8 E

Lat 38° 55' 58.09"

Long -88° 16' 31.6"

Local Grid Location ☐ N ☐ S Feet ☐ E ☐ W Feet

Facility ID	County Jasper	State IL	Civil Town/City/ or Village Newton



Sample: Number and Type	Sample: Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Soil Properties: Compressive Strength (tsf)	Soil Properties: Moisture Content	Soil Properties: Liquid Limit	Soil Properties: Plasticity Index	Soil Properties: P 200	RQD/ Comments
1 CS	120 113		0 - 0.4	0 - 0.4' **CLAYEY SILT** ML/CL, grayish brown (10YR 5/2) to brownish yellow (10YR 6/6), roots (5-15%), gravel (0-5%), no dilatancy, medium toughness, low plasticity, wet.	ML/CL									CS= Core Sample
			0.4 - 10	0.4 - 10' **LEAN CLAY:** CL, gray (10YR 6/1), strong brown (7.5YR 5/8) mottling (15-30%), brown (10YR 3/3), silt (15-30%), sand (0-5%), organic material (0-5%), no dilatancy, low toughness, medium plasticity, wet to moist.	CL									
2 SH	24 24		10 - 12	10 - 12' **LEAN CLAY:** CL.	CL					17.8	28	16	53.8	SH= Shelby Tube

I hereby certify that the information on this form is true and correct to the best of my knowledge.

Signature

Firm Ramboll
234 W. Florida Street, Milwaukee, WI 53204

Tel: (414) 837-3607
Fax: (414) 837-3608

Boring Number APW11

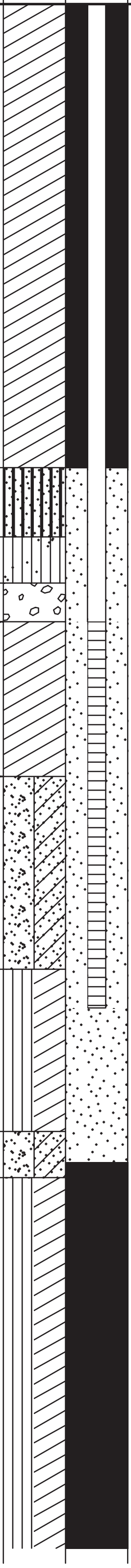
Page 2 of 6

Sample: Number and Type	Sample: Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Soil Properties: Compressive Strength (tsf)	Soil Properties: Moisture Content	Soil Properties: Liquid Limit	Soil Properties: Plasticity Index	Soil Properties: P 200	RQD/ Comments
3 CS	96 96			12 - 22.3' **SILT WITH SAND:** (ML)s, brown (10YR 5/3), clay (5-15%), gravel (0-5%), cohesive, low toughness, non-plastic to low plasticity, moist.										
			13											
			14											
			15	15' brown (10YR 4/3), clay (5-15%), gravel (5-15%), low to medium toughness.										
			16											
			17		(ML)s									
			18	18' sand seams (0-5%) 1/16" diameter.										
			19											
4 CS	120 120		20											
			21											
			22											
				22.3 - 28' **SILT:** ML, yellowish brown (10YR 5/4), grayish brown (10YR 5/2) mottling (0-5%), strong brown (7.5YR 5/6) mottling (0-5%), clay (15-30%), sand (0-5%), gravel (0-5%), no dilatancy, medium toughness, low plasticity.										
			23											
			24											
			25		ML									
			26											
			27											
			28	28 - 58' **LEAN CLAY:** CL, yellowish brown (10YR 5/4), grayish brown (10YR 5/2) mottling (0-5%), strong brown (7.5YR 5/6) mottling (0-5%), silt (15-30%), sand (0-5%), gravel (0-5%), no dilatancy, low toughness, medium to high plasticity.										
			29											
5 CS	120 120		30		CL									
			31											
			32											

Boring Number APW11

Sample		Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Soil Properties					RQD/ Comments
Number and Type	Length Att. & Recovered (in)								Compressive Strength (tsf)	Moisture Content	Liquid Limit	Plasticity Index	P 200	
				28 - 58' **LEAN CLAY:** CL, yellowish brown (10YR 5/4), grayish brown (10YR 5/2) mottling (0-5%), strong brown (7.5YR 5/6) mottling (0-5%), silt (15-30%), sand (0-5%), gravel (0-5%), no dilatancy, low toughness, medium to high plasticity. *(continued)*										
			33	33.2' - 34.4' gray (10YR 5/1) mottling (5-15%), sand (5-15%).										
			34	34.4' - 40' sand (5-15%).										
			35											
			36											
			37											
			38											
			39											
6 CS	120 120		40											
			41											
			42		CL									
			43											
			44											
			45											
			46											
			47											
			48	48.6' dark grayish brown (10YR 4/2), olive gray (5Y 4/2) mottling (5-15%), dark grayish brown (2.5Y 4/2) mottling (5-15%), dark reddish brown (5YR 3/4) mottling (0-5%),.										
			49											
7 CS	120 120		50											
			51											
			52											

Boring Number APW11



Sample Number and Type	Sample Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	PID 10.6 eV Lamp	Soil Properties Compressive Strength (tsf)	Moisture Content	Liquid Limit	Plasticity Index	P 200	RQD/ Comments
			53 54 55 56 57	28 - 58' **LEAN CLAY:** CL, yellowish brown (10YR 5/4), grayish brown (10YR 5/2) mottling (0-5%), strong brown (7.5YR 5/6) mottling (0-5%), silt (15-30%), sand (0-5%), gravel (0-5%), no dilatancy, low toughness, medium to high plasticity. *(continued)* 55.7' - 56.9' dark gray (10YR 4/1) to (7.5YR 4/1).	CL							
			58	58 - 58.9' **SILTY SAND:** SM, grayish brown (10YR 5/2), gravel (5-15%), dense, moist.	SM							
			59	58.9 - 59.5' **SILT WITH SAND:** (ML)s, grayish brown (10YR 5/2), dark yellowish brown (10YR 4/6) mottling (0-5%), clay (15-30%), gravel (0-5%), low toughness, low plasticity.	(ML)s							
8 MC	24 20		60 61	59.5 - 60' **POORLY-GRADED GRAVEL:** GP, grayish brown (10YR 5/2), subrounded to subangular, fine gravel, sand (30-45%), silt (15-30%), moist. 60 - 62' **LEAN CLAY:** CL.	GP CL			17.8	27	9	78.6	MC= Modified California Sample
9 CS	96 96		62 63 64	62 - 64.5' **POORLY-GRADED SAND WITH CLAY:** SP-SC, dark gray (10YR 4/1), subrounded, fine sand, dense, wet.	SP-SC							
			65 66	64.5 - 66.6' **CLAYEY SILT** ML/CL, dark gray (10YR 4/1), sand (0-5%), gravel (0-5%), no dilatancy, medium toughness, low to medium plasticity, moist.	ML/CL							
			67	66.6 - 67.2' **POORLY-GRADED SAND WITH CLAY:** SP-SC, dark gray (10YR 4/1), subrounded, fine sand, gravel (5-15%), dense, wet.	SP-SC							
			68 69	67.2 - 80' **CLAYEY SILT** to **SILTY CLAY:** ML/CL, dark gray (10YR 4/1), sand (0-5%), gravel (0-5%), no dilatancy, high toughness, medium plasticity, moist.	ML/CL							
10 CS	120 120		70 71 72									

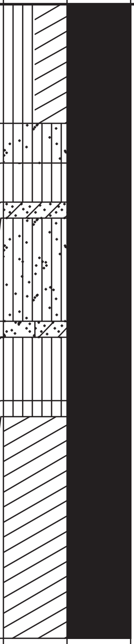
Boring Number APW11

Sample									Soil Properties					
Number and Type	Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Compressive Strength (tsf)	Moisture Content	Liquid Limit	Plasticity Index	P 200	RQD/ Comments
			73	67.2 - 80' **CLAYEY SILT** to **SILTY CLAY:** ML/CL, dark gray (10YR 4/1), sand (0-5%), gravel (0-5%), no dilatancy, high toughness, medium plasticity, moist. *(continued)*	ML/CL									
			74											
			75											
			76											
			77											
			78											
			79											
11 SH	24 24		80	80 - 82' **LEAN CLAY:** CL.	CL					16.5	32	18	79	
			81											
12 CS	96 96		82	82 - 93.5' **CLAYEY SILT** to **SILTY CLAY:** ML/CL, dark gray (10YR 4/1), sand (0-5%), gravel (0-5%), no dilatancy, high toughness, medium plasticity, moist.	ML/CL									
			83											
			84											
			85											
			86	86' olive (5Y 4/4), dark yellowish brown (10YR 4/6) mottling (5-15%), dark gray (10YR 4/1) mottling (0-5%), black (10YR 2/1) mottling (0-5%).										
			87	87.4' olive gray (5Y 4/2), dark gray (10YR 4/1) mottling (15-30%), organic material (0-5%).										
			88	88.5' dark gray (10YR 4/1), olive gray (5Y 4/2) mottling (5-15%), olive brown (2.5Y 4/4) mottling (0-5%).										
			89	89.7' olive (5Y 4/4).										
13 CS	120 120		90	90.2' olive gray (5Y 4/2), organic material (0-5%).										
			91											
			92											

SOIL BORING LOG INFORMATION SUPPLEMENT

Boring Number APW11

Sample									Soil Properties					
Number and Type	Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Compressive Strength (tsf)	Moisture Content	Liquid Limit	Plasticity Index	P 200	RQD/ Comments
			93	82 - 93.5' **CLAYEY SILT** to **SILTY CLAY:** ML/CL, dark gray (10YR 4/1), sand (0-5%), gravel (0-5%), no dilatancy, high toughness, medium plasticity, moist. *(continued)* 92' - 92.2' layer of organic material.	ML/CL									
			94	93.5 - 94' **SANDY SILT:** s(ML), dark gray (10YR 4/1), reddish brown (5YR 4/4) mottling (5-15%), clay (5-15%), gravel (0-5%), cohesive, non-plastic, moist.	s(ML)									
				94 - 94.5' **SILT:** ML, olive gray (5Y 4/2).	ML									
			95	94.5 - 94.7' **CLAYEY SAND:** SC, dark gray (10YR 4/1), wet.	SC									
			96	94.7 - 96' **SANDY SILT:** s(ML), dark gray (10YR 4/1), reddish brown (5YR 4/4) mottling (5-15%), clay (5-15%), gravel (0-5%), cohesive, non-plastic, moist.	s(ML)									
				96 - 96.2' **POORLY-GRADED SAND WITH CLAY:** SP-SC, dark gray (10YR 4/1), loose, moist.	SP-SC									
			97	96.2 - 97' **SILT:** ML, dark gray (10YR 4/1), clay (5-15%), sand (5-15%), no dilatancy to slow dilatancy, low toughness, medium plasticity.	ML									
			98	97 - 97.2' **SILT:** ML, very dark grayish brown (10YR 3/2), dry.	ML									
			99	97.2 - 100' **LEAN CLAY:** CL, dark gray (10R 4/1), silt (5-15%), organic material (0-5%), no dilatancy, high toughness, medium to high plasticity, moist.	CL									
			100	100' End of Boring.										



SOIL BORING LOG INFORMATION

Page 1 of 4

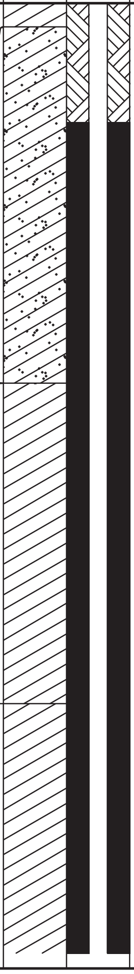
Facility/Project Name Newton Power Station	License/Permit/Monitoring Number	Boring Number APW12	
Boring Drilled By: Name of crew chief (first, last) and Firm Russ Gordon Cascade Drilling	Date Drilling Started 1/21/2021	Date Drilling Completed 2/21/2021	Drilling Method Mini Sonic
Common Well Name APW12	Final Static Water Level Feet (NAVD88)	Surface Elevation 543.33 Feet (NAVD88)	Borehole Diameter 6.0 inches

Local Grid Origin ☐ (estimated: ☐) or Boring Location ☒
State Plane 824,081.13 N, 1,001,683.34 E [✓ E]/ W
1/4 of 1/4 of Section 25, T 6 N, R 8 E

Lat 38° 55' 47.07"
Long -88° 16' 19.39"

Local Grid Location
Feet ☐ N ☐ S
Feet ☐ E ☐ W

Facility ID	County Jasper	State IL	Civil Town/City/ or Village Newton



Sample: Number and Type	Sample: Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Soil Properties: Compressive Strength (tsf)	Soil Properties: Moisture Content	Soil Properties: Liquid Limit	Soil Properties: Plasticity Index	Soil Properties: P 200	RQD/ Comments
1 CS	60 37		0	0 - 0.4' **LEAN CLAY:** CL, dark brown (10YR 3/3), sand (0-5%), roots (0-5%), moist.	CL									CS= Core Sample
			0.4	0.4 - 6.4' **SANDY LEAN CLAY:** s(CL), yellowish brown (10YR 5/6), gravel (0-5%), stiff, low plasticity, moist.	s(CL)									
			1						2					
			3						1.5					
2 CS	60 43		5											
			6						1.5					
			6.4	6.4 - 11.8' **LEAN CLAY:** CL, yellowish brown (10YR 5/6), gray and yellowish brown mottling (0-5%), sand (0-5%), stiff medium plasticity.	CL									
			7						1.5					
			8						1.5					
3 CS	60 60		10											
			11						1					
			11.8	11.8 - 20' **LEAN CLAY:** to **SILTY CLAY:** CL, yellowish brown (10YR 5/6), gray and yellowish brown mottling (0-5%), gravel (0-5%), sand (0-5%), very stiff, medium plasticity, moist.	CL									
			12						2					
			13						2.5					
			14						2					
4 CS	60 60		15	15' hard, gray and yellowish brown mottling (15-25%).					2.5					
			16											

I hereby certify that the information on this form is true and correct to the best of my knowledge.

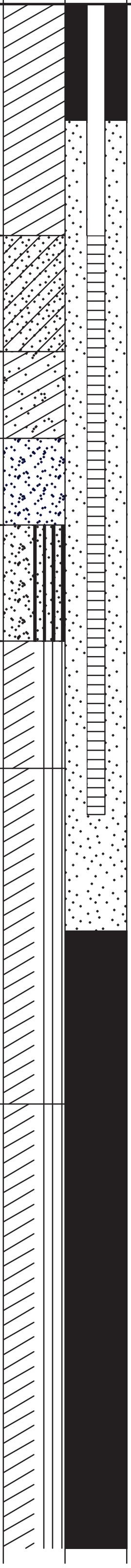
Signature	Firm Ramboll 234 W. Florida Street, Milwaukee, WI 53204	Tel: (414) 837-3607 Fax: (414) 837-3608

SOIL BORING LOG INFORMATION SUPPLEMENT

Boring Number APW12

Page 2 of 4

Sample: Number and Type	Sample: Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	PID 10.6 eV Lamp	Soil Properties: Compressive Strength (tsf)	Soil Properties: Moisture Content	Soil Properties: Liquid Limit	Soil Properties: Plasticity Index	Soil Properties: P 200	RQD/ Comments
			17 18 19	11.8 - 20' **LEAN CLAY:** to **SILTY CLAY:** CL, yellowish brown (10YR 5/6), gray and yellowish brown mottling (0-5%), gravel (0-5%), sand (0-5%), very stiff, medium plasticity, moist. *(continued)*	CL		4.5 4.5 4.5 4.5					
5 SH	24 24		20 21	20 - 22' **CLAYEY SAND:** SC.	SC			15.1	27	15	45.8	SH= Shelby Tube
6 CS	36 36		22 23	22 - 23.5' **SANDY LEAN CLAY:** s(CL), yellowish brown (10YR 5/6), silt (15-25%), gravel (0-5%), hard, low plasticity, wet.	s(CL)		4.5					
			24	23.5 - 25' **POORLY-GRADED SAND:** SP, yellowish brown (10YR 5/6), fine to medium sand, gravel (0-5%), silt (0-5%), wet.	SP							
7 MC	24 24		25 26	25 - 27' **POORLY-GRADED SAND WITH SILT:** SP-SM.	SP-SM			8.4	10		6.2	MC= Modified California Sample
8 CS	36 36		27 28 29	27 - 29.2' **SILTY CLAY:** CL/ML, yellowish brown (10YR 5/6), sand (15-25%), gravel (15-25%), hard, low plasticity, dry.	CL/ML		4.5					
9 CS	60 60		30 31 32	29.2 - 35' **SILTY CLAY:** CL/ML, dark gray (10YR 4/1), gravel (15-25%), sand (0-5%), hard, low plasticity, dry.	CL/ML		4.5					
			33 34	32.6' - 34' sand (15-25%).								
10 CS	60 60		35 36 37 38 39	35 - 55' **SILTY CLAY:** CL/ML, yellowish brown (10YR 5/6), yellowish brown and gray mottling (0-5%), gravel (15-25%), sand (0-25%), hard, low plasticity, dry.	CL/ML		4.5 4.5 4.5					
11 CS	60 60		40 41				4.5					
			42	41.7' - 43.2' gravel (15-45%).								



Boring Number APW12

Sample: Number and Type	Sample: Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Soil Properties: Compressive Strength (tsf)	Soil Properties: Moisture Content	Soil Properties: Liquid Limit	Soil Properties: Plasticity Index	Soil Properties: P 200	RQD/ Comments
			43	35 - 55' **SILTY CLAY:** CL/ML, yellowish brown (10YR 5/6), yellowish brown and gray mottling (0-5%), gravel (15-25%), sand (0-25%), hard, low plasticity, dry. *(continued)*					4.5					
			44											
12 CS	60 60		45						4.5					
			46											
			47						4.5					
			48											
			49		CL/ML				4.5					
13 CS	60 60		50											
			51						4.5					
			52						4.5					
			53											
			54											
14 CS	60 60		55	55 - 56.4' **SILTY CLAY:** CL/ML, dark gray (10YR 4/1), yellowish brown mottling (0-5%), sand (0-5%), hard, medium plasticity, moist.	CL/ML									
			56						4.5					
			57	56.4 - 58.6' **SILT:** ML, dark gray (10YR 4/1), clay (15-25%), sand (0-5%), moist.										
			58	58.4' - 58.6' layer of clayey sand.	ML									
			59	58.6 - 70.8' **LEAN CLAY:** to **SILTY CLAY:** CL, dark gray (10YR 4/1), gravel (15-25%), sand (0-5%), hard, low plasticity, dry.					4.5					
15 CS	60 60		60											
			61						4.5					
			62											
			63						4.5					
			64		CL									
16 CS	60 60		65						4.5					
			66											
			67						4.5					
			68											
			69											

Boring Number APW12

Sample									Soil Properties					
Number and Type	Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Compressive Strength (tsf)	Moisture Content	Liquid Limit	Plasticity Index	P 200	RQD/ Comments
17 CS	60 60		70	58.6 - 70.8' **LEAN CLAY: to SILTY CLAY:** CL, dark gray (10YR 4/1), gravel (15-25%), sand (0-5%), hard, low plasticity, dry. *(continued)*	CL				4.5					
			71 72	70.8 - 72.6' **SILT:** ML, dark gray (10YR 4/1), sand (0-5%), dry to moist.	ML									
			73 74	72.6 - 74' **SILTY CLAY:** CL/ML, dark gray (10YR 4/1), sand (0-5%), gravel (0-5%), hard, low plasticity, dry.	CL/ML									
18 CS	60 60		75 76 77	74 - 77.5' **SILT:** ML, dark gray (10YR 4/1), sand (0-5%), dry.	ML									
19 CS	60 60		78 79 80 81 82 83 84 85	77.5 - 85' **SILTY CLAY:** CL/ML, gray (10YR 4/1), sand (0-5%), gravel (0-5%), dry.	CL/ML									
20 SH	24 24		86 87	85 - 87' **LEAN CLAY:** CL.	CL					14.4	29	15	80.2	
				87' End of Boring.										

SOIL BORING LOG INFORMATION

Page 1 of 4

Facility/Project Name Newton Power Station	License/Permit/Monitoring Number	Boring Number APW13

Boring Drilled By: Name of crew chief (first, last) and Firm Russ Gordon Cascade Drilling	Date Drilling Started 1/22/2021	Date Drilling Completed 1/22/2021	Drilling Method Mini Sonic

Common Well Name APW13	Final Static Water Level Feet (NAVD88)	Surface Elevation 535.16 Feet (NAVD88)	Borehole Diameter 6.0 inches

Local Grid Origin ☐ (estimated: ☐) or Boring Location ☒

State Plane 822,591.02 N, 1,001,013.30 E [✓ E]/ W

1/4 of 1/4 of Section 25, T 6 N, R 8 E

Lat 38° 55' 32.35"

Long -88° 16' 27.88"

Local Grid Location: Feet ☐ N ☐ S; Feet ☐ E ☐ W

Facility ID	County Jasper	State IL	Civil Town/City/ or Village Newton

Sample: Number and Type	Sample: Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Soil Properties: Compressive Strength (tsf)	Soil Properties: Moisture Content	Soil Properties: Liquid Limit	Soil Properties: Plasticity Index	Soil Properties: P 200	RQD/ Comments
1 CS	60 60			0 - 0.4' **SILTY SAND:** SM, dark brown (10YR 3/3), clay (15-25%), moist.	SM									CS= Core Sample
			1 2	0.4 - 2.3' **SILTY CLAY:** CL/ML, yellowish brown (10YR 5/6), gray mottling (0-5%), sand (0-5%), gravel (0-5%), firm to stiff, medium plasticity, moist.	CL/ML				1					
2 CS	60 60		3 4 5 6	2.3 - 6.2' **SILTY CLAY:** to **LEAN CLAY:** CL/ML, yellowish brown (10YR 5/6), sand (0-5%), gravel (0-5%), stiff, low plasticity, moist.	CL/ML				2 2 1.5					
			7 8	6.2 - 8.7' **SANDY LEAN CLAY:** (CL)g, yellowish brown (10YR 5/6), gravel (0-5%), stiff, low plasticity, moist. 6.5' yellowish brown and gray mottling (15-25%).	(CL)g				1.5 1.5					
			9 10	8.7 - 10' **SILTY CLAY:** to **LEAN CLAY:** CL/ML, yellowish brown (10YR 5/6), sand (0-5%), gravel (0-5%), stiff, low plasticity, moist.	CL/ML				1.5					
3 CS	60 60		11 12 13	10 - 13.8' **SANDY LEAN CLAY:** (CL)g, yellowish brown (10YR 5/6), gravel (15-25%), hard, low plasticity, moist. 10.8' - 11.1' layer of clayey sand.	(CL)g				2 4.5					
4 CS	60 60		14 15 16	13.8 - 22.1' **SILT:** ML, dark gray (10YR 4/1), clay (0-25%), sand (0-5%), gravel (0-5%), hard, dry.	ML									

I hereby certify that the information on this form is true and correct to the best of my knowledge.

Signature	Firm Ramboll 234 W. Florida Street, Milwaukee, WI 53204	Tel: (414) 837-3607 Fax: (414) 837-3608

RAMBOLL

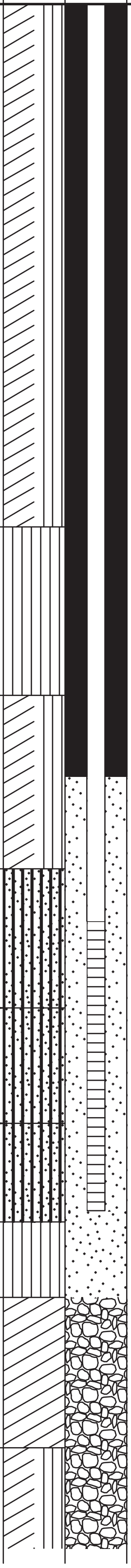
SOIL BORING LOG INFORMATION SUPPLEMENT

Boring Number APW13

Page 2 of 4

Sample: Number and Type	Sample: Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Soil Properties: Compressive Strength (tsf)	Soil Properties: Moisture Content	Soil Properties: Liquid Limit	Soil Properties: Plasticity Index	Soil Properties: P 200	RQD/ Comments
			17	13.8 - 22.1' **SILT:** ML, dark gray (10YR 4/1), clay (0-25%), sand (0-5%), gravel (0-5%), hard, dry. *(continued)*										
			18	17.8' clay (0-5%).										
			19		ML									
5 CS	60 60		20											
			21											
			22	22.1 - 25' **SILTY CLAY:** CL/ML, dark gray (10YR 4/1), gravel (0-5%), sand (0-5%), hard, low plasticity, dry.					4.5					
			23											
			24		CL/ML									
6 SH	24 24		25	25 - 27' **POORLY-GRADED SAND WITH SILT:** SP-SM.						21.2	9		11.1	SH= Shelby Tube
			26		SP-SM									
7 CS	36 36		27	27 - 31.2' **SILTY CLAY:** CL/ML, dark gray (10YR 4/1), gravel (0-5%), sand (0-5%), hard, low plasticity, dry. 27.8' - 28' layer of sand, moist.					4.5					
			28											
			29		CL/ML				4.5					
8 CS	60 60		30											
			31	31.2 - 35' **SILTY CLAY:** CL/ML, yellowish brown (10YR 5/6), yellowish brown and gray mottling (0-5%), gravel (15-25%), sand (0-5%), hard, low plasticity, dry.					4.5					
			32											
			33		CL/ML				4.5					
			34											
9 CS	60 60		35	35 - 51.7' **SILTY CLAY:** CL/ML, brown (10YR 5/3), gravel (0-5%), sand (0-5%), hard, low plasticity, dry.										
			36											
			37	37.2' - 38.3' gray mottling (15-25%).										
			38											
			39		CL/ML									
10 CS	60 60		40	40' very stiff to hard, medium plasticity.										
			41						3					
			42						3.5					

Boring Number APW13



Sample: Number and Type	Sample: Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	PID 10.6 eV Lamp	Soil Properties: Compressive Strength (tsf)	Soil Properties: Moisture Content	Soil Properties: Liquid Limit	Soil Properties: Plasticity Index	Soil Properties: P 200	RQD/ Comments
			43	35 - 51.7' **SILTY CLAY:** CL/ML, brown (10YR 5/3), gravel (0-5%), sand (0-5%), hard, low plasticity, dry. *(continued)*	CL/ML		4.5					
			44				3.5					
11 CS	60 60		45				4.5					
			46				4.5					
			47				3.5					
			48				3.5					
			49				4.5					
12 CS	60 60		50				4.5					
			51				4.5					
			52	51.7 - 54.6' **SILT:** ML, brown (10YR 5/3), gray mottling (15-25%), sand (0-5%), gravel (0-5%).	ML							
			53									
			54									
13 CS	60 60		55	54.6 - 57.6' **SILTY CLAY:** CL/ML, brown (10YR 5/3), sand (0-5%), gravel (0-5%), hard, low plasticity.	CL/ML		4.5					
			56									
			57									
			58	57.6 - 60' **SILTY SAND:** SM, brown (10YR 5/3), fine sand, clay (0-5%), wet.	SM							
			59									
14 MC	24 24		60	60 - 62' **SILTY SAND:** SM.	SM			14.5	8		24.5	MC= Modified California Sample
			61									
15 CS	96 96		62	62 - 63.7' **SILTY SAND:** SM, brown (10YR 5/3), fine sand, clay (0-5%), wet. 62.5' - 63.1' layer of silt.	SM							
			63									
			64	63.7 - 65' **SILT:** ML, brown (10YR 5/3), sand (0-5%), clay (0-5%), dry.	ML							
			65	65 - 67.6' **LEAN CLAY:** CL, dark gray (10YR 4/1), silt (15-25%), sand (0-5%), stiff to very stiff, medium plasticity, dry.	CL		2					
			66				2					
			67									
			68	67.6 - 89.7' **SILTY CLAY:** CL/ML, dark gray (10YR 4/1), gravel (15-25%), sand (15-25%), hard, low plasticity, dry.	CL/ML		4.5					
			69									

SOIL BORING LOG INFORMATION SUPPLEMENT

Boring Number APW13

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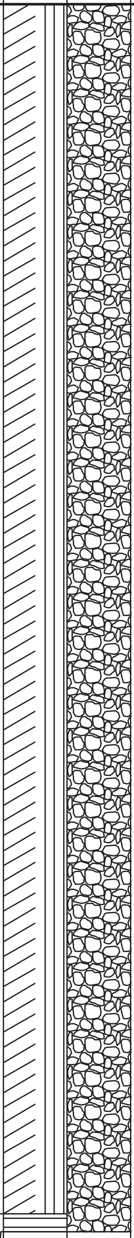
Sample Number and Type	Sample Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Soil Properties Compressive Strength (tsf)	Soil Properties Moisture Content	Soil Properties Liquid Limit	Soil Properties Plasticity Index	Soil Properties P 200	RQD/ Comments
16 CS	120 120		70	67.6 - 89.7' **SILTY CLAY:** CL/ML, dark gray (10YR 4/1), gravel (15-25%), sand (15-25%), hard, low plasticity, dry. *(continued)* 70' dark green mottling, gravel (0-5%).					4.5					
			71						4.5					
			72											
			73						4.5					
			74											
			75						4.5					
			76											
			77						4.5					
			78											
			79						4.5					
17 CS	120 120		80		CL/ML									
			81											
			82											
			83											
			84											
			85											
			86											
			87											
			88											
			89											
			90	89.7 - 90' **SHALE:** BDX (SH), black (10YR 2/1). 90' End of Boring.	BDX (SH)									



R000814

SOIL BORING LOG INFORMATION

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Facility/Project Name Newton Power Station	License/Permit/Monitoring Number	Boring Number APW14

Boring Drilled By: Name of crew chief (first, last) and Firm Adam Jochimsen Cascade Drilling	Date Drilling Started 1/23/2021	Date Drilling Completed 1/23/2021	Drilling Method Mini Sonic
Common Well Name APW14	Final Static Water Level Feet (NAVD88)	Surface Elevation 523.85 Feet (NAVD88)	Borehole Diameter 6.0 inches

Local Grid Origin ☐ (estimated: ☐) or Boring Location ☒

State Plane 822,006.47 N, 999,995.70 E [✓ E]/ W

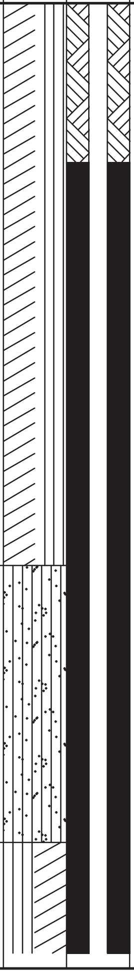
1/4 of 1/4 of Section 25, T 6 N, R 8 E

Lat 38° 55' 26.58"

Long -88° 16' 40.76"

Local Grid Location ☐ N ☐ S Feet ☐ E ☐ W Feet

Facility ID	County Jasper	State IL	Civil Town/City/ or Village Newton



Sample: Number and Type	Sample: Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Soil Properties: Compressive Strength (tsf)	Soil Properties: Moisture Content	Soil Properties: Liquid Limit	Soil Properties: Plasticity Index	Soil Properties: P 200	RQD/ Comments
1 CS	60 51			0 - 7.1' **SILTY CLAY:** CL/ML, yellowish brown (10YR 5/4), yellowish brown (10YR 5/6) mottling (10-20%), gray (10YR 5/1) mottling (0-5%), sand (0-5%), gravel (0-5%), very stiff, no dilatancy, medium toughness, medium plasticity, moist.										CS= Core Sample
			1						3					
			2											
			3						3.5					
			4		CL/ML									
2 CS	60 53		5						2.5					
			6											
			7						0.5					
				7.1 - 10.6' **SILTY SAND:** s(ML), yellowish brown (10YR 5/6), clay (5-10%), soft, slow dilatancy, low toughness, low plasticity, moist.										
			8											
			9		s(ML)									
3 CS	60 57		10											
				10.6 - 14.2' **CLAYEY SILT** ML/CL, brown (10YR 5/3), sand (5-10%), gravel (0-5%), hard, no dilatancy, medium toughness, low plasticity, dry.										
			11		ML/CL				4.5					
			12											

I hereby certify that the information on this form is true and correct to the best of my knowledge.

Signature	Firm Ramboll 234 W. Florida Street, Milwaukee, WI 53204	Tel: (414) 837-3607 Fax: (414) 837-3608

Template: RAMBOLL_IL_BORING LOG - Project: 845_NEWTON_2021 (1).GPJ

SOIL BORING LOG INFORMATION SUPPLEMENT

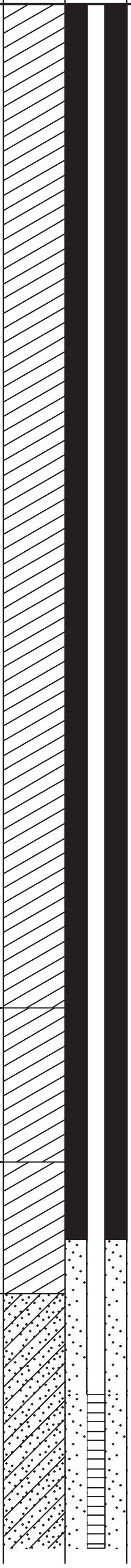
Boring Number APW14

Sample: Number and Type	Sample: Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Soil Properties: Compressive Strength (tsf)	Soil Properties: Moisture Content	Soil Properties: Liquid Limit	Soil Properties: Plasticity Index	Soil Properties: P 200	RQD/ Comments
			13	10.6 - 14.2' **CLAYEY SILT** ML/CL, brown (10YR 5/3), sand (5-10%), gravel (0-5%), hard, no dilatancy, medium toughness, low plasticity, dry. *(continued)*	ML/CL				4					
			14	14.2 - 15' **SILTY SAND:** SM, yellowish brown (10YR 5/6), subrounded to rounded, medium to fine sand, loose, moist.	SM									
4 CS	60 57		15	15 - 45' **LEAN CLAY:** CL, gray (10YR 5/1), silt (15-25%), sand (5-10%), gravel (0-5%), hard, no dilatancy, medium toughness, medium plasticity, dry to moist.					4					
			16											
			17						4.5					
			18											
			19						4.5					
5 CS	120 104		20	20' yellowish brown (10YR 5/6) mottling (15-20%).										
			21						3.5					
			22											
			23		CL				3					
			24											
			25						3.5					
			26											
			27						4					
			28											
			29						4.5					
6 CS	60 60		30	30' silt stringers 1mm to 3mm diameter in fractures.										
			31						4.5					
			32											

SOIL BORING LOG INFORMATION SUPPLEMENT

Boring Number APW14

Sample: Number and Type	Sample: Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	PID 10.6 eV Lamp	Soil Properties: Compressive Strength (tsf)	Soil Properties: Moisture Content	Soil Properties: Liquid Limit	Soil Properties: Plasticity Index	Soil Properties: P 200	RQD/ Comments
			33	15 - 45' **LEAN CLAY:** CL, gray (10YR 5/1), silt (15-25%), sand (5-10%), gravel (0-5%), hard, no dilatancy, medium toughness, medium plasticity, dry to moist. *(continued)*			4.5					
			34									
7 CS	60 60		35				4.5					
			36									
			37				4.5					
			38		CL							
			39				4.5					
8 CS	60 60		40									
			41				4.5					
			42									
			43				4.5					
			44									
9 SH	24 24		45	45 - 47' **LEAN CLAY:** CL.	CL			12.4	26	12	63.3	SH= Shelby Tube
			46									
10 CS	96 94		47	47 - 48.7' **LEAN CLAY:** CL, gray (10YR 5/1), yellowish brown (10YR 5/6) mottling (15-20%), silt (15-25%), sand (5-10%), gravel (0-5%), hard, no dilatancy, medium toughness, medium plasticity, dry to moist.	CL		4.5					
			48									
			49	48.7 - 55' **CLAYEY SAND:** to **SANDY LEAN CLAY WITH GRAVEL:** SC, dark grayish brown (10YR 4/2), subrounded to rounded, medium sand, dense, moist.	SC		4.5					
			50									
			51				2.25					
			52									



SOIL BORING LOG INFORMATION SUPPLEMENT

Boring Number APW14

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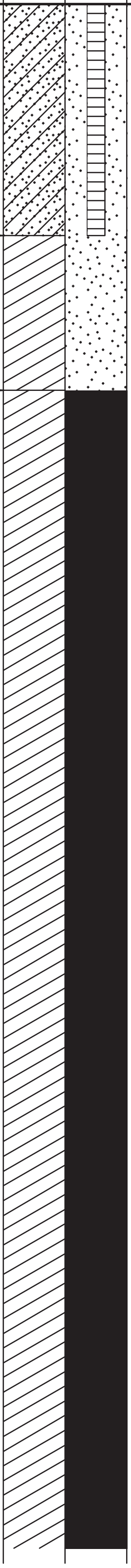

Sample Number and Type	Sample Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	PID 10.6 eV Lamp	Compressive Strength (tsf)	Moisture Content	Liquid Limit	Plasticity Index	P 200	RQD/ Comments
			53 54	48.7 - 55' **CLAYEY SAND:** to **SANDY LEAN CLAY WITH GRAVEL:** SC, dark grayish brown (10YR 4/2), subrounded to rounded, medium sand, dense, moist. *(continued)*	SC							
11 MC	24 24		55 56	55 - 57' **LEAN CLAY:** CL.	CL			18	25	10	72.2	MC= Modified California Sample
12 CS	96 96		57 58	57 - 91' **LEAN CLAY:** CL, gray (10YR 5/1), yellowish brown (10YR 5/6) mottling (0-5%), silt (15-25%), sand (5-10%), gravel (0-5%), organic material (0-5%), very stiff to hard, no dilatancy, medium toughness, medium plasticity, dry.			3.75					
			59 60				4.25					
			61 62				4.25					
			63 64				4.25					
13 CS	120 120		65 66		CL		4					
			67 68				2.25					
			69 70				4.5					
			71 72				4.5					

SOIL BORING LOG INFORMATION SUPPLEMENT

Boring Number APW14 Page 5 of 6

Sample Number and Type	Sample Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Compressive Strength (tsf)	Moisture Content	Liquid Limit	Plasticity Index	P 200	RQD/ Comments
				57 - 91' **LEAN CLAY:** CL, gray (10YR 5/1), yellowish brown (10YR 5/6) mottling (0-5%), silt (15-25%), sand (5-10%), gravel (0-5%), organic material (0-5%), very stiff to hard, no dilatancy, medium toughness, medium plasticity, dry. *(continued)*										
			73						4.5					
			74											
14 CS	120 120		75						4.5					
			76											
			77						4.5					
			78											
			79						4					
			80											
			81						4.25					
			82		CL									
			83						2.5					
			84	83.7' greenish gray (GLEY1 6/5GY) mottling (10-15%), yellowish brown (10YR 5/6) mottling (10-15%), stiff.										
15 CS	60 46		85						2.75					
			86											
			87						3					
			88											
			89						3.5					
16 CS	60 56		90											
			91	91 - 95' **Weathered SHALE Bedrock** BDX (SH), gray (10YR 6/1) to grayish brown (10YR 5/2).	BDX (SH)				4.5					
			92											

R000819

SOIL BORING LOG INFORMATION SUPPLEMENT

Boring Number APW14

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Sample									Soil Properties					
Number and Type	Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Compressive Strength (tsf)	Moisture Content	Liquid Limit	Plasticity Index	P 200	RQD/ Comments
			93 94 95	91 - 95' **Weathered SHALE Bedrock** BDX (SH), gray (10YR 6/1) to grayish brown (10YR 5/2). *(continued)*	BDX (SH)									
				95' End of Boring.										

SOIL BORING LOG INFORMATION

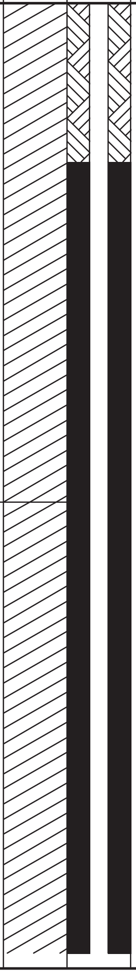
Page 1 of 6

Facility/Project Name Newton Power Station	License/Permit/Monitoring Number	Boring Number APW15

Boring Drilled By: Name of crew chief (first, last) and Firm Adam Jochimsen Cascade Drilling	Date Drilling Started 1/21/2021	Date Drilling Completed 1/22/2021	Drilling Method Mini Sonic
Common Well Name APW15	Final Static Water Level Feet (NAVD88)	Surface Elevation 522.06 Feet (NAVD88)	Borehole Diameter 6.0 inches

Local Grid Origin ☐ (estimated: ☐) or Boring Location ☒
State Plane 821,107.90 N, 997,938.87 E [✓ E]/ W
1/4 of 1/4 of Section 26, T 6 N, R 8 E
Lat 38° 55' 17.71"
Long -88° 17' 6.79"
Local Grid Location Feet ☐ N ☐ S Feet ☐ E ☐ W

Facility ID	County Jasper	State IL	Civil Town/City/ or Village Newton



Sample: Number and Type	Sample: Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Soil Properties: Compressive Strength (tsf)	Soil Properties: Moisture Content	Soil Properties: Liquid Limit	Soil Properties: Plasticity Index	Soil Properties: P 200	RQD/ Comments
1 CS	60 54		1 2 3 4	0 - 6.3' **FILL, LEAN CLAY:** CL, brown (10YR 5/3), silt (15-25%) sand (0-5%), stiff, no dilatancy, low toughness, medium plasticity, moist.	(FILL) CL				1.75 1.75					CS= Core Sample
2 CS	60 40		5 6											
			7 8 9	6.3 - 20' **LEAN CLAY:** CL, dark gray (10YR 4/1), silt (15-25%) sand (0-5%), gravel (0-5%), organic material (0-5%), very stiff to stiff, no dilatancy, medium toughness, medium plasticity, moist.	CL				2.25 4					
3 CS	60 50		10 11 12						1					

I hereby certify that the information on this form is true and correct to the best of my knowledge.

Signature

Firm Ramboll
234 W. Florida Street, Milwaukee, WI 53204
Tel: (414) 837-3607
Fax: (414) 837-3608

Boring Number APW15

Sample: Number and Type	Sample: Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Soil Properties: Compressive Strength (tsf)	Soil Properties: Moisture Content	Soil Properties: Liquid Limit	Soil Properties: Plasticity Index	Soil Properties: P 200	RQD/ Comments
			13	6.3 - 20' **LEAN CLAY:** CL, dark gray (10YR 4/1), silt (15-25%) sand (0-5%), gravel (0-5%), organic material (0-5%), very stiff to stiff, no dilatancy, medium toughness, medium plasticity, moist. *(continued)*					2.5					
			14											
4 CS	60 54		15						1.5					
			16		CL									
			17						2.25					
			18											
			19	19.2' brown (10YR 4/3), yellowish brown (10YR 5/6) mottling (10-15%), stiff.					2.5					
5 SH	24 23		20	20 - 22' **LEAN CLAY:** CL.						18.5	33	23	59.2	SH= Shelby Tube
			21		CL									
6 CS	96 96		22	22 - 23.5' **LEAN CLAY:** CL, brown (10YR 4/3), yellowish brown (10YR 5/6) mottling (10-15%), stiff, no dilatancy, medium toughness, medium plasticity, moist.	CL				1.25					
			23						1					
			24	23.5 - 26.7' **SANDY LEAN CLAY:** s(CL), brown (10YR 5/3), gray (10YR 5/1) mottling (5-10%), stiff, slow dilatancy, low toughness, medium plasticity, moist.										
			25		s(CL)				3.75					
			26											
			27	26.7 - 39.2' **LEAN CLAY:** CL, brown (10YR 5/3), yellowish brown (10YR 5/6) mottling (10-15%), gray (10YR 5/1) mottling (5-10%), sand (5-10%), gravel (0-5%), cobbles (0-5%), very stiff to hard, no dilatancy, medium toughness, medium plasticity, dry to moist.					4.5					
			28											
			29		CL				4.5					
6 CS	60 49		30	30' hard, dry.										
			31						4.5					
			32											

Boring Number APW15

Sample									Soil Properties					
Number and Type	Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Compressive Strength (tsf)	Moisture Content	Liquid Limit	Plasticity Index	P 200	RQD/ Comments
			33	26.7 - 39.2' **LEAN CLAY:** CL, brown (10YR 5/3), yellowish brown (10YR 5/6) mottling (10-15%), gray (10YR 5/1) mottling (5-10%), sand (5-10%), gravel (0-5%), cobbles (0-5%), very stiff to hard, no dilatancy, medium toughness, medium plasticity, dry to moist. *(continued)*					4.5					
			34											
7 CS	60 49		35						4.5					
			36		CL									
			37						4.5					
			38											
			39						4.5					
8 CS	60 60		40	39.2 - 52.5' **LEAN CLAY:** CL, dark gray (10YR 4/1), no mottling, organic material (0-5%), sand (5-10%), gravel (0-5%), cobbles (0-5%), hard, no dilatancy, medium toughness, medium plasticity, dry, silt stringers 1mm to 3mm diameter fracture planes.										
			41						4.5					
			42											
			43						4.5					
			44											
9 CS	60 60		45						4.5					
			46		CL									
			47						4.5					
			48											
			49						4.5					
10 CS	60 60		50											
			51						4.5					
			52											

SOIL BORING LOG INFORMATION SUPPLEMENT

Boring Number APW15

Sample Number and Type	Sample Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Soil Properties Compressive Strength (tsf)	Soil Properties Moisture Content	Soil Properties Liquid Limit	Soil Properties Plasticity Index	Soil Properties P 200	RQD/ Comments
			53	52.5 - 61.4' **SILT:** ML, dark gray (10YR 4/1), clay (15-25%), hard, no dilatancy, medium toughness, non-plastic, dry.					4.5					
			54											
11 CS	60 57		55						4.5					
			56											
			57		ML				4.5					
			58											
			59						4.5					
12 CS	60 52		60											
			61						4.5					
			62	61.4 - 97.2' **LEAN CLAY:** CL, dark gray (10YR 4/1), silt (15-25%), sand (0-10%), gravel (0-5%), organic material (0-5%), stiff to very stiff, no dilatancy, medium toughness, medium plasticity, moist to dry.										
			63						2.75					
			64											
13 CS	60 60		65						2.75					
			66											
			67		CL				2.25					
			68											
			69						2					
14 CS	60 60		70											
			71						2.5					
			72											

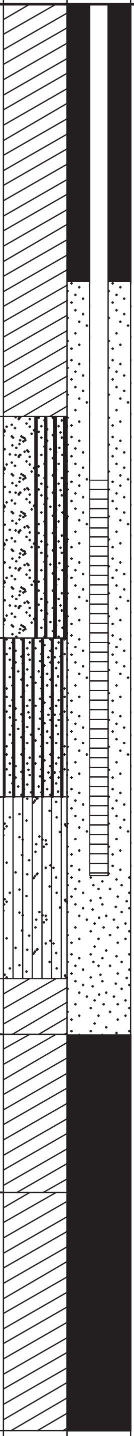
SOIL BORING LOG INFORMATION SUPPLEMENT

Boring Number APW15

Sample: Number and Type	Sample: Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Soil Properties: Compressive Strength (tsf)	Soil Properties: Moisture Content	Soil Properties: Liquid Limit	Soil Properties: Plasticity Index	Soil Properties: P 200	RQD/ Comments
				61.4 - 97.2' **LEAN CLAY:** CL, dark gray (10YR 4/1), silt (15-25%), sand (0-10%), gravel (0-5%), organic material (0-5%), stiff to very stiff, no dilatancy, medium toughness, medium plasticity, moist to dry. *(continued)*										
			73						2.5					
			74											
15 CS	60 53		75						2					
			76											
			77						2.5					
			78											
			79						2.25					
16 CS	60 60		80											
			81						2.25					
			82		CL									
			83						4.5					
			84	83.8' - 83.9' layer of silty sand, moist.										
17 CS	60 60		85	85' - 85.4' later of silty sand, moist.					2.75					
			86											
			87						2.5					
			88											
			89						2.75					
18 CS	60 60		90											
			91						2.5					
			92											

SOIL BORING LOG INFORMATION SUPPLEMENT

Boring Number APW15



Sample									Soil Properties					
Number and Type	Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Compressive Strength (tsf)	Moisture Content	Liquid Limit	Plasticity Index	P 200	RQD/ Comments
19 CS	60 60		93 94 95 96 97	61.4 - 97.2' **LEAN CLAY:** CL, dark gray (10YR 4/1), silt (15-25%), sand (0-10%), gravel (0-5%), organic material (0-5%), stiff to very stiff, no dilatancy, medium toughness, medium plasticity, moist to dry. *(continued)*	CL				2.75					
			98 99	97.2 - 100' **POORLY-GRADED SAND WITH SILT:** SP-SM, dark gray (10YR 4/1), subrounded to rounded, medium to fine sand, loose, wet.	SP-SM									
20 SH	24 24		100 101	100 - 102' **SILTY SAND:** SM.	SM					12.1	15	3	45.8	
21 CS	36 36		102 103 104	102 - 104.3' **SANDY SILT:** s(ML), gray (10YR 5/1), firm, slow dilatancy, low toughness, non-plastic, wet.	s(ML)				1					
				104.3 - 105' **LEAN CLAY:** CL, dark gray (10YR 4/1), sand (5-10%), gravel (0-5%), organic material (0-5%), stiff to very stiff, medium toughness, medium plasticity, moist.	CL									
22 MC	24 24		105 106	105 - 107' **LEAN CLAY:** CL.	CL					19.1	29	16	76.2	MC= Modified California Sample
23 CS	36 36		107 108 109	107 - 110' **LEAN CLAY:** CL, dark gray (10YR 4/1), sand (5-10%), gravel (0-5%), organic material (0-5%), stiff to very stiff, no dilatancy, medium toughness, medium plasticity, moist.	CL				2.25 2.5					
			110	110' End of Boring.										

SOIL BORING LOG INFORMATION

Facility/Project Name Newton Power Station	License/Permit/Monitoring Number	Boring Number APW16

Boring Drilled By: Name of crew chief (first, last) and Firm Adam Jochimsen Cascade Drilling	Date Drilling Started 1/19/2021	Date Drilling Completed 1/20/2021	Drilling Method Mini Sonic
Common Well Name APW16	Final Static Water Level Feet (NAVD88)	Surface Elevation 529.16 Feet (NAVD88)	Borehole Diameter 6.0 inches

Local Grid Origin ☐ (estimated: ☐) or Boring Location ☒

State Plane 820,642.46 N, 996,213.53 E [✓ E]/ W

1/4 of 1/4 of Section 35, T 6 N, R 8 E

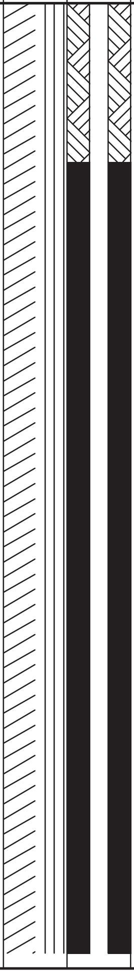
Lat 38° 55' 13.12"

Long -88° 17' 28.63"

Local Grid Location ☐ N ☐ S Feet ☐ E ☐ W Feet

Facility ID	County Jasper	State IL	Civil Town/City/ or Village Newton

Sample									Soil Properties					
Number and Type	Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Compressive Strength (tsf)	Moisture Content	Liquid Limit	Plasticity Index	P 200	RQD/ Comments
1 CS	60 48		1 2	0 - 20' **SILTY CLAY:** CL/ML, yellowish brown (10YR 5/4), gray (10YR 5/1) mottling (0-5%), sand (0-5%), gravel (0-5%), firm to stiff, slow dilatancy, medium to low toughness, medium plasticity, moist.					0.75					CS= Core Sample
			3 4						1.75					
2 CS	60 60		5 6	5' very dark grayish brown (10YR 3/2) mottling (0-5%), yellowish brown (10YR 5/6) mottling (0-5%), silt stringers 1mm diameter (5-10%), very stiff, dry.	CL/ML				2					
			7 8						3.5					
			9						3.75					
3 CS	60 60		10 11 12	10' hard.					4.5					



I hereby certify that the information on this form is true and correct to the best of my knowledge.

Signature	Firm Ramboll 234 W. Florida Street, Milwaukee, WI 53204	Tel: (414) 837-3607 Fax: (414) 837-3608

RAMBØLL

SOIL BORING LOG INFORMATION SUPPLEMENT

Boring Number APW16

Sample: Number and Type	Sample: Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Soil Properties: Compressive Strength (tsf)	Soil Properties: Moisture Content	Soil Properties: Liquid Limit	Soil Properties: Plasticity Index	Soil Properties: P 200	RQD/ Comments
			13	0 - 20' **SILTY CLAY:** CL/ML, yellowish brown (10YR 5/4), gray (10YR 5/1) mottling (0-5%), sand (0-5%), gravel (0-5%), firm to stiff, slow dilatancy, medium to low toughness, medium plasticity, moist. *(continued)*					4.5					
			14											
4 CS	60 60		15	15' grayish brown (10YR 5/2), yellowish brown (10YR 5/6) mottling (5-10%).					4.5					
			16		CL/ML									
			17						4.5					
			18											
			19						4.5					
5 CS	120 65		20	20 - 30' **SILT:** ML, brown (10YR 5/3), yellowish brown (10YR 5/6) mottling (5-10%), sand (5-10%), gravel (0-5%), hard, no dilatancy, high toughness, low plasticity, dry.										
			21						4.5					
			22											
			23						4.5					
			24											
			25		ML				4.5					
			26											
			27						4.5					
			28											
			29						4.5					
6 CS	60 57		30	30 - 69.2' **SILTY CLAY:** CL/ML, dark gray (10YR 4/1), sand (5-10%), gravel (0-5%), cobbles (0-5%), hard to very stiff, no dilatancy, medium toughness, medium plasticity, dry to moist.										
			31		CL/ML				4.5					
			32											

Boring Number APW16 Page 3 of 6

Sample Number and Type	Sample Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Soil Properties Compressive Strength (tsf)	Soil Properties Moisture Content	Soil Properties Liquid Limit	Soil Properties Plasticity Index	Soil Properties P 200	RQD/ Comments
				30 - 69.2' **SILTY CLAY:** CL/ML, dark gray (10YR 4/1), sand (5-10%), gravel (0-5%), cobbles (0-5%), hard to very stiff, no dilatancy, medium toughness, medium plasticity, dry to moist. *(continued)*										
			33						4.25					
			34											
7 CS	60 60		35						4					
			36											
			37						4.5					
			38											
			39						4.5					
8 CS	60 60		40											
			41						4.5					
				41.5' organic material (0-5%), wood (0-5%).										
			42		CL/ML									
			43						4.5					
			44											
9 CS	60 60		45						4.5					
			46											
			47						4.25					
			48											
			49						4.25					
10 CS	60 60		50											
			51						4.5					
			52											

SOIL BORING LOG INFORMATION SUPPLEMENT

Boring Number APW16

Sample: Number and Type	Sample: Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Soil Properties: Compressive Strength (tsf)	Soil Properties: Moisture Content	Soil Properties: Liquid Limit	Soil Properties: Plasticity Index	Soil Properties: P 200	RQD/ Comments
			53	30 - 69.2' **SILTY CLAY:** CL/ML, dark gray (10YR 4/1), sand (5-10%), gravel (0-5%), cobbles (0-5%), hard to very stiff, no dilatancy, medium toughness, medium plasticity, dry to moist. *(continued)*					4.5					
			54											
11 CS	60 60		55						4.5					
			56											
			57						3.75					
			58											
			59						3.75					
12 CS	60 60		60											
			61		CL/ML				4.5					
			62											
			63						3.75					
			64											
13 CS	180 45		65						2.25					
			66											
			67						1.25					
			68											
			69						0.25					
			70	69.2 - 70.6' **SILT WITH SAND:** (ML)s, gray (10YR 6/1), soft, rapid dilatancy, low toughness, non-plastic, wet.	(ML)s									
			71	70.6 - 85.6' **POORLY-GRADED SAND:** SP, gray (10YR 5/1), subrounded to rounded, medium to coarse sand, gravel (0-5%), loose, wet.	SP									
			72											

Boring Number APW16

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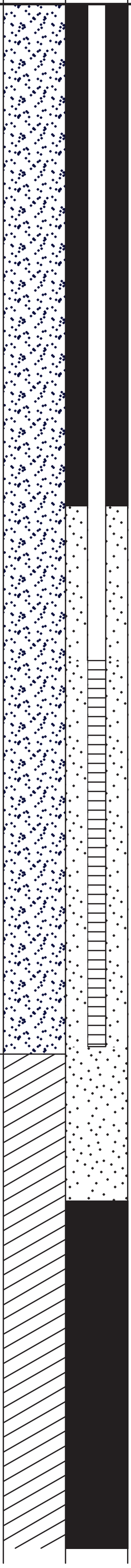


Sample: Number and Type	Sample: Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	PID 10.6 eV Lamp	Soil Properties: Compressive Strength (tsf)	Soil Properties: Moisture Content	Soil Properties: Liquid Limit	Soil Properties: Plasticity Index	Soil Properties: P 200	RQD/ Comments
				70.6 - 85.6' **POORLY-GRADED SAND:** SP, gray (10YR 5/1), subrounded to rounded, medium to coarse sand, gravel (0-5%), loose, wet. *(continued)*								
			73									
			74									
			75									
			76									
			77									
			78									
			79		SP							
14 CS	60 60		80									
			81									
			82									
			83									
			84									
15 CS	120 120		85	85' gravel (10-15%).								
			86	85.6 - 99.2' **LEAN CLAY:** CL, gray (10YR 5/1), silt (5-15%), sand (5-10%), gravel (0-5%), very stiff, no dilatancy, medium toughness, medium plasticity, moist.								
			87				3.5					
			88									
			89		CL		2.75					
			90									
			91				3.25					
			92									

Sample: Number and Type	Sample: Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Soil Properties: Compressive Strength (tsf)	Soil Properties: Moisture Content	Soil Properties: Liquid Limit	Soil Properties: Plasticity Index	Soil Properties: P 200	RQD/ Comments
			93	85.6 - 99.2' **LEAN CLAY:** CL, gray (10YR 5/1), silt (5-15%), sand (5-10%), gravel (0-5%), very stiff, no dilatancy, medium toughness, medium plasticity, moist. *(continued)*					3.25					
			94											
16 CS	60 48		95						3.5					
			96		CL									
			97						2.5					
			98											
			99						2.25					
				99.2 - 100' **POORLY-GRADED SAND:** SP, dark gray (10YR 4/1), subrounded to rounded, coarse sand, loose, wet.	SP									
17 CS	120 120		100	100 - 110' **LEAN CLAY:** CL, gray (10YR 5/1), silt (5-15%), sand (5-10%), organic material (0-10%), gravel (0-5%), very stiff, no dilatancy, medium toughness, medium plasticity, moist.										
			101						2					
			102											
			103						1.75					
			104											
			105		CL				2					
			106											
			107						2					
			108											
			109						2					
			110	110' End of Boring.										

SOIL BORING LOG INFORMATION

Page 1 of 5

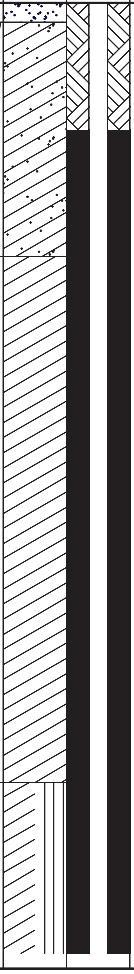
Facility/Project Name Newton Power Station	License/Permit/Monitoring Number	Boring Number APW17

Boring Drilled By: Name of crew chief (first, last) and Firm Dave Gordon Cascade Drilling	Date Drilling Started 1/22/2021	Date Drilling Completed 1/22/2021	Drilling Method Mini Sonic
Common Well Name APW17	Final Static Water Level Feet (NAVD88)	Surface Elevation 529.84 Feet (NAVD88)	Borehole Diameter 6.0 inches

Local Grid Origin ☐ (estimated: ☐) or Boring Location ☒
State Plane 822,681.14 N, 995,462.29 E [✓ E]/ W
1/4 of 1/4 of Section 26, T 6 N, R 8 E
Lat 38° 55' 33.27"
Long -88° 17' 38.12"
Local Grid Location
Feet ☐ N ☐ S Feet ☐ E ☐ W

Facility ID	County Jasper	State IL	Civil Town/City/ or Village Newton

Sample: Number and Type	Sample: Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Soil Properties: Compressive Strength (tsf)	Soil Properties: Moisture Content	Soil Properties: Liquid Limit	Soil Properties: Plasticity Index	Soil Properties: P 200	RQD/ Comments
1 CS	120 120			0 - 0.3' **POORLY-GRADED SAND WITH SILT:** SP, yellowish brown (10YR 5/8), subrounded, fine sand, roots (15-30%), clay (5-15%), gravel (5-15%), loose, wet.	SP									CS= Core Sample
			1 2 3	0.3 - 4' **LEAN CLAY WITH SAND:** (CL)s, yellowish brown (10YR 5/8), grayish brown (10YR 5/2) mottling (15-30%), gravel (0-5%), roots (0-5%), rapid dilatancy, low toughness, low to medium plasticity, wet.	(CL)s									
2 CS	120 108		4 5 6 7 8 9 10 11 12	4 - 12.3' **LEAN CLAY:** CL, yellowish brown (10YR 5/6), dark yellowish brown (10R 4/4) mottling (0-5%), silt (15-30%), sand (5-15%), gravel (0-5%), roots (0-5%), organic material (0-5%), slow dilatancy, medium toughness, low plasticity, moist. 7.5' dry. 11.6' - 11.8' layer of gravel with clay, wet. 12.2' layer of sand for 1/8".	CL									
			13 14 15	12.3 - 26.3' **SILTY CLAY:** CL/ML, dark grayish brown (10YR 4/2), strong brown (10YR 5/8) mottling (5-15%), sand (0-5%), no dilatancy, medium toughness, low plasticity, dry sand seams 1/16" (0-5%).	CL/ML									



I hereby certify that the information on this form is true and correct to the best of my knowledge.

Signature

Firm Ramboll
234 W. Florida Street, Milwaukee, WI 53204
Tel: (414) 837-3607
Fax: (414) 837-3608

SOIL BORING LOG INFORMATION SUPPLEMENT

Boring Number APW17

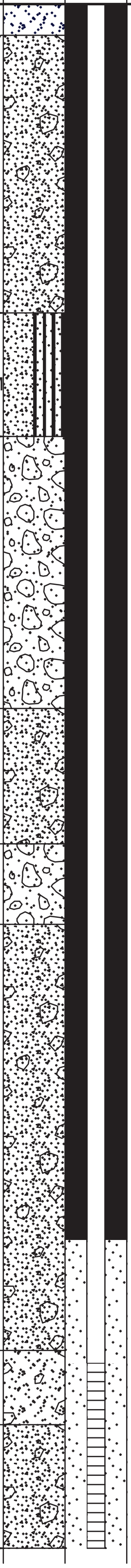
Sample									Soil Properties					
Number and Type	Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Compressive Strength (tsf)	Moisture Content	Liquid Limit	Plasticity Index	P 200	RQD/ Comments
3 CS	240 240		16 17 18 19 20 21 22 23 24 25 26	12.3 - 26.3' **SILTY CLAY:** CL/ML, dark grayish brown (10YR 4/2), strong brown (10YR 5/8) mottling (5-15%), sand (0-5%), no dilatancy, medium toughness, low plasticity, dry sand seams 1/16" (0-5%). *(continued)* 16.5' white (10YR 8/1) for 1/16".	CL/ML									
				26' - 26.3' layer of silt, yellowish brown (10YR 5/4) to (10YR 5/6), sand (5-15%), dry.										
			27 28 29 30 31 32 33 34 35 36 37 38 39 40	26.3 - 40' **CLAYEY SILT** ML/CL, dark grayish brown (10YR 4/2), yellowish brown (10YR 5/4) mottling (5-15%), sand (5-15%), gravel (0-5%), no dilatancy, high toughness, non-plastic to low plasticity, dry to moist.	ML/CL									

Boring Number APW17 Page 3 of 5

Sample: Number and Type	Sample: Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Compressive Strength (tsf)	Soil Properties: Moisture Content	Soil Properties: Liquid Limit	Soil Properties: Plasticity Index	Soil Properties: P 200	RQD/ Comments
4 SH	24 21		40	40 - 42' **LEAN CLAY:** CL.	CL					16.6	26	13	71.1	SH= Shelby Tube
5 CS	96 96		42	42 - 43' **CLAYEY SILT** ML/CL, dark grayish brown (10YR 4/2), yellowish brown (10YR 5/4) mottling (5-15%), sand (5-15%), gravel (0-5%), no dilatancy, high toughness, non-plastic to low plasticity, dry to moist.	ML/CL									
			43	43 - 44.5' **CLAYEY SILT** ML/CL, dark grayish brown (10YR 4/2) to grayish brown (10YR 5/2), sand (5-15%), gravel (0-5%), no dilatancy, high toughness, non-plastic to low plasticity, dry to moist.	ML/CL									
			44.5	44.5 - 46.3' **SILT WITH SAND:** (ML)s, gray (10YR 5/1) to grayish brown (10YR 5/2), clay (5-15%), moist.	(ML)s									
			46.3	46.3 - 58' **CLAYEY SILT** ML/CL, dark grayish brown (10YR 4/2) to grayish brown (10YR 5/2), sand (5-15%), gravel (0-5%), no dilatancy, high toughness, non-plastic to low plasticity, dry to moist.	ML/CL									
6 CS	120 118		50											
			58	58 - 63.3' **SILT WITH SAND:** (ML)s, dark grayish brown (10YR 4/2) to grayish brown (10YR 5/2), clay (5-15%), gravel (0-5%), non-cohesive to cohesive, no dilatancy, medium to high toughness, non-plastic to low plasticity, moist.	(ML)s									
7 CS	120 120		60											
			63.3	63.3 - 64.7' **WELL-GRADED SAND:** SW, gray (10YR 5/1), subangular to subrounded, gravel (5-15%), clay (5-15%), wet.	SW									
			65											

SOIL BORING LOG INFORMATION SUPPLEMENT

Boring Number APW17



Sample: Number and Type	Sample: Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	PID 10.6 eV Lamp	Soil Properties: Compressive Strength (tsf)	Soil Properties: Moisture Content	Soil Properties: Liquid Limit	Soil Properties: Plasticity Index	Soil Properties: P 200	RQD/ Comments
			64.7 - 65.5	64.7 - 65.5' **POORLY-GRADED SAND WITH SILT:** SP, gray (10YR 5/1) to grayish brown (10YR 5/2), subrounded, fine to medium sand, gravel (5-15%), wet. *(continued)*	SP							
			65.5 - 70	65.5 - 70' **WELL-GRADED SAND WITH GRAVEL:** (SW)g, gray (10YR 5/1), subangular to subrounded, gravel (5-15%), clay (0-5%), cobbles (0-5%), moist to wet. 68.5' - 69' cobbles (5-15%). 69.6' very dark gray (10YR 3/1).	(SW)g							
8 MC	24 24		70 - 72	70 - 72' **WELL-GRADED SAND WITH SILT:** SW-SM.	SW-SM			7.8	3.8	9	8.9	MC= Modified California Sample
9 CS	216 216		72 - 76.4	72 - 76.4' **WELL-GRADED GRAVEL WITH SAND:** (GW)s, gray (10YR 5/1), subrounded to rounded gravel, cobbles (5-15%), clay (5-15%), dense, wet.	(GW)s							
			76.4 - 78.6	76.4 - 78.6' **WELL-GRADED SAND WITH GRAVEL:** (SW)g, gray (10YR 5/1), cobbles (0-5%), dense, wet.	(SW)g							
			78.6 - 79.9	78.6 - 79.9' **WELL-GRADED GRAVEL WITH SAND:** (GW)s, gray (10YR 5/1) to grayish brown (10YR 5/2), subrounded to rounded gravel, cobbles (5-15%), clay (5-15%), dense, wet.	(GW)s							
			79.9 - 86.8	79.9 - 86.8' **WELL-GRADED SAND WITH GRAVEL:** (SW)g, grayish brown (10YR 5/2), clay (0-5%), cobbles (0-5%), dense, wet to moist.	(SW)g							
			86.8 - 88	86.8 - 88' **POORLY-GRADED SAND WITH GRAVEL:** (SP)g, grayish brown (10YR 5/2), rounded to subrounded, medium to coarse sand, clay (0-5%), loose, wet.	(SP)g							
			88 - 90	88 - 90' **WELL-GRADED SAND WITH GRAVEL:** (SW)g, silt (5-15%), loose, wet to moist.	(SW)g							

SOIL BORING LOG INFORMATION SUPPLEMENT

Boring Number APW17

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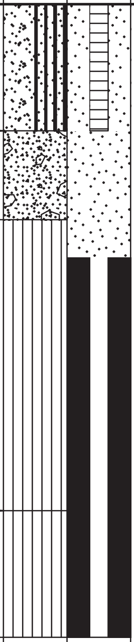


Sample Number and Type	Sample Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Soil Properties Compressive Strength (tsf)	Moisture Content	Liquid Limit	Plasticity Index	P 200	RQD/ Comments
10 MC	24 24		91	90 - 92' **POORLY-GRADED SAND WITH SILT:** SP-SM.	SP-SM					6.1	6		6.7	
11 CS	72 72		92 93	92 - 93.4' **WELL-GRADED SAND WITH GRAVEL:** (SW)g, silt (5-15%), loose, wet to moist.	(SW)g									
			94 95 96 97	93.4 - 98' **SILT:** ML, dark gray (10YR 4/1) to gray (10YR 5/1), very dark gray (10YR 3/1) mottling (0-5%), clay (15-30%), sand (5-15%), gravel (0-5%), organic material (0-5%), no dilatancy, high toughness, low plasticity, moist.	ML									
12 SH	24 24		98 99	98 - 100' **SILT:** ML, Not Analyzed.	ML									
			100	100' End of Boring.										

SOIL BORING LOG INFORMATION

Page 1 of 6

Facility/Project Name Newton Power Station	License/Permit/Monitoring Number	Boring Number APW18

Boring Drilled By: Name of crew chief (first, last) and Firm Dave Gordon Cascade Drilling	Date Drilling Started 1/20/2021	Date Drilling Completed 1/21/2021	Drilling Method Mini Sonic

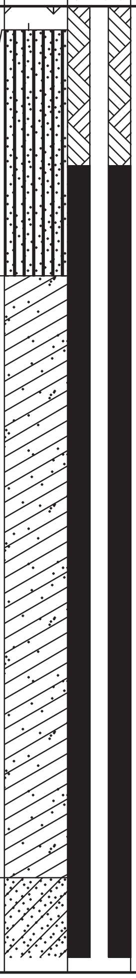
Common Well Name APW18	Final Static Water Level Feet (NAVD88)	Surface Elevation 540.55 Feet (NAVD88)	Borehole Diameter 6.0 inches

Local Grid Origin ☐ (estimated: ☐) or Boring Location ☒
State Plane 824,525.91 N, 996,544.05 E [✓ E]/ W
1/4 of 1/4 of Section 26, T 6 N, R 8 E

Lat 38° 55' 51.5"
Long -88° 17' 24.42"

Local Grid Location
Feet ☐ N ☐ S
Feet ☐ E ☐ W

Facility ID	County Jasper	State IL	Civil Town/City/ or Village Newton



Sample: Number and Type	Sample: Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Soil Properties: Compressive Strength (tsf)	Soil Properties: Moisture Content	Soil Properties: Liquid Limit	Soil Properties: Plasticity Index	Soil Properties: P 200	RQD/ Comments
1 CS	120 113			0 - 0.3' **FILL, SILT:** ML, dark grayish brown (10R 4/2), roots (15-30%), sand (5-15%), wet.	(FILL) ML									CS= Core Sample
			1 2 3	0.3 - 3.4' **SILTY SAND:** SM, yellowish brown (10YR 5/6), dark grayish brown (10YR 4/2) mottling (15-30%), fine sand, gravel (0-5%), roots (0-5%), dense, moist.	SM									
			4 5 6 7 8 9	3.4 - 11' **LEAN CLAY WITH SAND:** (CL)s, yellowish brown (10YR 5/6), dark grayish brown (10YR 4/2) mottling (5-15%), strong brown (7.5YR 5/8) mottling (5-15%), slow dilatancy, low toughness, low to medium plasticity, moist.	(CL)s									
2 CS	120 113		10											
			11 12	11 - 12.5' **CLAYEY SAND:** SC, dark yellowish brown (10YR 4/6), rounded, fine sand, gravel (0-5%), wet.	SC									

I hereby certify that the information on this form is true and correct to the best of my knowledge.

Signature

Firm Ramboll
234 W. Florida Street, Milwaukee, WI 53204
Tel: (414) 837-3607
Fax: (414) 837-3608

SOIL BORING LOG INFORMATION SUPPLEMENT

Boring Number APW18

Sample									Soil Properties					
Number and Type	Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Compressive Strength (tsf)	Moisture Content	Liquid Limit	Plasticity Index	P 200	RQD/ Comments
				11.6' medium sand.										
			13	12.5 - 13.9' **LEAN CLAY WITH SAND:** (CL)s, yellowish brown (10YR 5/6), slow dilatancy, low toughness, low to medium plasticity, wet.	(CL)s									
			14 15 16	13.9 - 16.8' **SILT:** ML, dark grayish brown (10YR 4/2), clay (15-30%), sand (5-15%), gravel (0-5%), no dilatancy, low to medium toughness, low plasticity, dry.	ML									
			17	16.8 - 17.6' **POORLY-GRADED SAND:** SP, yellowish brown (10YR 5/6), rounded, fine sand, clay (5-15%), moist.	SP									
			18 19	17.6 - 20' **SILT:** ML, dark grayish brown (10YR 4/2), yellowish brown (10YR 5/6) mottling (0-5%), very dark grayish brown (10YR 3/2) mottling (0-5%), clay (15-30%), sand (5-15%), gravel (0-5%), no dilatancy, low to medium toughness, low plasticity, dry.	ML									
3 CS	120 120		20	20 - 20.9' **WELL-GRADED SAND:** SW, yellowish brown (10YR 5/6), clay (5-15%), gravel (0-5%), wet.	SW									
			21 22 23	20.9 - 23.2' **CLAYEY SILT** ML/CL, dark grayish brown (10YR 4/2), yellowish brown (10YR 5/6) mottling (0-5%), very dark grayish brown (10YR 3/2) mottling (0-5%), clay (15-30%), sand (5-15%), gravel (0-5%), no dilatancy, low to medium toughness, low plasticity, moist.	ML/CL									
				23.2 - 23.7' **WELL-GRADED SAND:** SW, subrounded, fine sand, gravel (5-15%), silt (5-15%), moist.	SW									
			24 25 26 27 28	23.7 - 28.9' **LEAN CLAY:** CL, dark gray (10YR 4/1), sand (5-15%), gravel (0-5%), no dilatancy, medium toughness, high plasticity, moist. 28.2' sand (0-5%).	CL									
4 CS	120 120		29 30 31 32	28.9 - 50' **CLAYEY SILT** ML/CL, dark gray (10YR 4/1), sand (5-15%), gravel (0-5%), no dilatancy, high toughness, medium plasticity, dry.	ML/CL									

Boring Number APW18

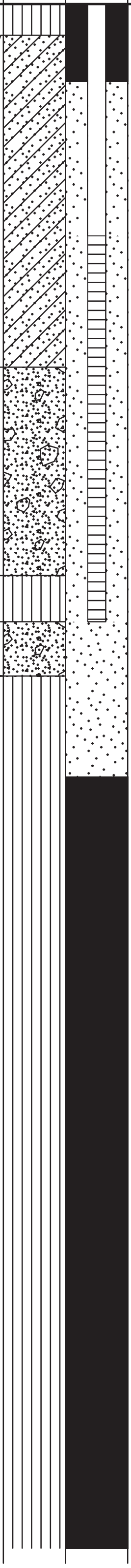
Sample		Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Soil Properties					RQD/ Comments
Number and Type	Length Att. & Recovered (in)								Compressive Strength (tsf)	Moisture Content	Liquid Limit	Plasticity Index	P 200	
5 CS	120 120		33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49	28.9 - 50' **CLAYEY SILT** ML/CL, dark gray (10YR 4/1), sand (5-15%), gravel (0-5%), no dilatancy, high toughness, medium plasticity, dry. *(continued)*	ML/CL									
6 SH	24 24		50 51 52	50 - 52' **LEAN CLAY:** CL.	CL					12.9	32	20	76.8	SH= Shelby Tube

SOIL BORING LOG INFORMATION SUPPLEMENT

Boring Number APW18

Sample									Soil Properties					
Number and Type	Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Compressive Strength (tsf)	Moisture Content	Liquid Limit	Plasticity Index	P 200	RQD/ Comments
7 CS	96 96		52	52 - 58.2' **CLAYEY SILT** ML/CL, dark gray (10YR 4/1), sand (5-15%), gravel (0-5%), no dilatancy, high toughness, medium plasticity, dry.	ML/CL									
			58.2	58.2 - 60' **POORLY-GRADED SAND:** SP, gray (10YR 6/1) to light gray (10YR 7/1), subrounded, fine to medium sand, gravel (0-5%), silt (0-5%), loose, dry to moist.	SP									
8 MC	24 12		60	60 - 62' **SILTY SAND:** SM.	SM					13.6	5		17.1	MC= Modified California Sample
9 MC	24 16		62	62 - 64' **SILTY CLAY:** CL/ML.	CL/ML					11.1	20	6	57.6	
10 CS	72 72		64	64 - 67.5' **SANDY SILT:** s(ML), dark grayish brown (10YR 4/2), clay (0-5%), non-cohesive, moist.	s(ML)									
			67.5	67.5 - 70' **SILT:** ML, dark gray (10YR 4/1), clay (15-30%), sand (5-15%), gravel (0-5%), medium to high toughness, low plasticity, moist to wet.	ML									
11 SH	24 11		70	70 - 72' **SILT:** ML, Not Analyzed.	ML									
			72											

Boring Number APW18



Sample Number and Type	Sample Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Compressive Strength (tsf)	Moisture Content	Liquid Limit	Plasticity Index	P 200	RQD/ Comments
12 CS	96 92		72	72 - 72.4' **SILT:** ML, dark grayish brown (10YR 4/2), clay (15-30%), sand (5-15%), gravel (0-5%), medium to high toughness, low plasticity, moist to wet.	ML									
			73	72.4 - 76.7' **CLAYEY SAND:** SC, rounded, fine sand, dense, wet.	SC									
			77	76.7 - 79.4' **WELL-GRADED SAND WITH GRAVEL:** (SW)g, subrounded to subangular, silt (0-5%), moist.	(SW)g									
			79	79.4 - 80' **SILT:** ML, dark gray (10YR 4/1), clay (15-30%), sand (5-15%), gravel (0-5%), medium to high toughness, low plasticity, moist to wet.	ML									
13 CS	120 72		80	80 - 80.7' **WELL-GRADED SAND WITH GRAVEL:** (SW)g, subrounded to subangular, silt (0-5%), wet.	(SW)g									
			81	80.7 - 94.2' **SILT:** ML, dark gray (10YR 4/1), clay (15-30%), sand (5-15%), gravel (0-5%), medium to high toughness, low plasticity, moist.	ML									
14 CS	180 180		90											
			92											

SOIL BORING LOG INFORMATION SUPPLEMENT

Boring Number APW18

Page 6 of 6

Sample									Soil Properties					
Number and Type	Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Compressive Strength (tsf)	Moisture Content	Liquid Limit	Plasticity Index	P 200	RQD/ Comments
			93 94	80.7 - 94.2' **SILT:** ML, dark gray (10YR 4/1), clay (15-30%), sand (5-15%), gravel (0-5%), medium to high toughness, low plasticity, moist. *(continued)*	ML									
			95 96 97 98 99 100 101 102 103 104	94.2 - 105' **CLAYEY SILT** ML/CL, dark gray (10YR 4/1) to dark grayish brown (10YR 4/2), sand (5-15%), gravel (5-15%), slow dilatancy, medium toughness, low plasticity, moist. 97.4' grayish brown (10YR 5/2), reddish gray (5YR 5/2) mottling (0-5%), yellowish brown (10YR 5/6) mottling (0-5%).	ML/CL									
15 SH	24 24		105 106	105 - 107' **LEAN CLAY:** CL.	CL					14.1	28	15	69.3	
			107	107' End of Boring.										

RAMBOLL

SOIL BORING LOG INFORMATION

Page 1 of 2

Facility/Project Name Newton Power Station	License/Permit/Monitoring Number	Boring Number APW5S

Boring Drilled By: Name of crew chief (first, last) and Firm Dave Gordon Cascade Drilling	Date Drilling Started 1/19/2021	Date Drilling Completed 1/19/2021	Drilling Method Mini Sonic

Common Well Name APW5S	Final Static Water Level Feet (NAVD88)	Surface Elevation 541.05 Feet (NAVD88)	Borehole Diameter 6.0 inches

Local Grid Origin ☐ (estimated: ☐) or Boring Location ☒

State Plane 825,612.15 N, 999,129.20 E [✓ E]/ W

1/4 of 1/4 of Section 26, T 6 N, R 8 E

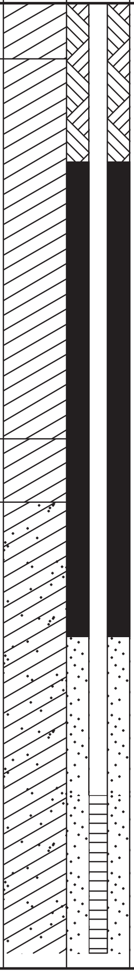
Lat 38° 55' 2.22"

Long -88° 16' 51.7"

Local Grid Location

Feet ☐ N ☐ S Feet ☐ E ☐ W

Facility ID	County Jasper	State IL	Civil Town/City/ or Village Newton



Sample: Number and Type	Sample: Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Soil Properties: Compressive Strength (tsf)	Soil Properties: Moisture Content	Soil Properties: Liquid Limit	Soil Properties: Plasticity Index	Soil Properties: P 200	RQD/ Comments
1 CS	120 115			0 - 0.7' **FILL, LEAN CLAY:** CL, very dark gray (10YR 3/1), yellowish brown (10YR 5/4) mottling (30-45%), roots (5-15%), sand (5-15%), gravel (0-5%), very stiff, no dilatancy, low to medium toughness, low plasticity, wet.	(FILL) CL									CS= Core Sample
			1 2 3 4 5	0.7 - 5.5' **FILL, LEAN CLAY:** CL, yellowish brown (10YR 5/4), gray (10YR 5/1) mottling (0-5%), sand (0-5%), gravel (0-5%), very stiff to stiff, no dilatancy , medium toughness, low plasticity, moist. 2.8' - 2.9' black (10YR 2/1), black (2.5Y 2.5/1) mottling (0-5%), coal (0-5%). 3.1' strong brown (7.5YR 5/6), gray (10YR 5/1) mottling (0-5%), black (10YR 2/1) mottling (0-5%), sand (5-15%), gravel (0-5%).	(FILL) CL				3.25 3.25 3.25					
			6	5.5 - 6.3' **LEAN CLAY:** CL, grayish brown (10YR 5/2) to brown (10YR 5/3), light olive brown (2.5Y 5/6) mottling (15-30%), stiff, no dilatancy, low toughness, medium plasticity, moist. 5.9' no mottling.	CL									
			7 8 9	6.3 - 14.3' **LEAN CLAY WITH SAND:** (CL)s, gray (10YR 5/1), organic material (0-5%), stiff to firm, no dilatancy, low toughness, medium plasticity, moist.	(CL)s				2 2.25					
2 CS	36 36		10 11 12						2					

I hereby certify that the information on this form is true and correct to the best of my knowledge.

Signature

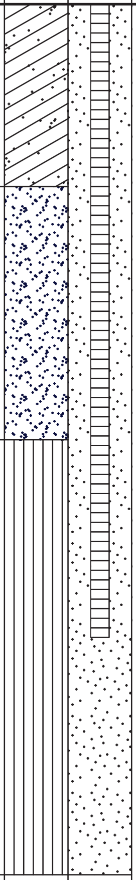
Firm Ramboll
234 W. Florida Street, Milwaukee, WI 53204

Tel: (414) 837-3607
Fax: (414) 837-3608

SOIL BORING LOG INFORMATION SUPPLEMENT

Boring Number APW5S

Page 2 of 2



Sample									Soil Properties					
Number and Type	Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Compressive Strength (tsf)	Moisture Content	Liquid Limit	Plasticity Index	P 200	RQD/ Comments
3 CS	120 94		13 14	6.3 - 14.3' **LEAN CLAY WITH SAND:** (CL)s, gray (10YR 5/1), organic material (0-5%), stiff to firm, no dilatancy, low toughness, medium plasticity, moist. *(continued)* 12.4' yellowish brown (10YR 5/6), gravel (0-5%).	(CL)s				0.75					
			15 16 17	14.3 - 17.5' **POORLY-GRADED SAND:** SP, yellowish brown (10YR 5/6) , subrounded to rounded, fine sand, clay (5-15%), gravel (0-5%), moist.	SP									
			18 19 20 21 22 23	17.5 - 23' **SILT:** ML, yellowish brown (10YR 5/6) to dark gray (10YR 4/1), strong brown (7.5YR 4/6) mottling (5-15%), very dark gray (7.5YR 3/1) mottling (0-5%), clay (5-15%), sand (5-15%), gravel (0-5%), very stiff to hard, no dilatancy, medium to high toughness, low plasticity. 19.4' yellowish brown (10YR 5/6), gray (10YR 5/1) mottling (0-5%).	ML				4.5 4 3.5					
				23' End of Boring.										

SOIL BORING LOG INFORMATION

Facility/Project Name Newton Power Station	License/Permit/Monitoring Number	Boring Number SB301

Boring Drilled By: Name of crew chief (first, last) and Firm Dave Gordon Cascade Drilling	Date Drilling Started 1/19/2021	Date Drilling Completed 1/20/2021	Drilling Method Mini Sonic
Common Well Name	Final Static Water Level Feet (NAVD88)	Surface Elevation 543.39 Feet (NAVD88)	Borehole Diameter 6.0 inches

Local Grid Origin ☐ (estimated: ☐) or Boring Location ☒

State Plane 825,067.09 N, 997,264.71 E [✓ E]/ W

1/4 of 1/4 of Section 25, T 6 N, R 8 E

Lat ____ ° ____ ' ______ "

Long ____ ° ____ ' ______ "

Local Grid Location ☐ N ☐ S Feet ☐ E ☐ W Feet

Facility ID	County Jasper	State IL	Civil Town/City/ or Village Newton

Sample: Number and Type	Sample: Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Soil Properties: Compressive Strength (tsf)	Soil Properties: Moisture Content	Soil Properties: Liquid Limit	Soil Properties: Plasticity Index	Soil Properties: P 200	RQD/ Comments
1 CS	120 99		1 2	0 - 2.6' **FILL, POORLY-GRADED SAND WITH GRAVEL:** (SP)g, black (10YR 2/1), loose. 1.8' - 2.2' layer of clay, dark grayish brown (10YR 4/2), silt (15-30%), sand (5-15%), low toughness, low plasticity, moist.	(FILL) (SP)g									CS= Core Sample
			3 4 5 6	2.6 - 6.5' **SILTY CLAY:** CL/ML, brown (10YR 5/3) to light olive brown (2.5Y 5/3), olive (5Y 4/3) mottling (15-30%), dark olive gray (5Y 3/2) mottling (0-5%), sand (0-5%), gravel (0-5%), roots (0-5%), stiff to very stiff, no dilatancy, low toughness, low plasticity, moist. 4.5' medium toughness.	CL/ML				1.75 3.5					
			7 8	6.5 - 9' **LEAN CLAY:** CL, gray (10YR 5/1), dark yellowish brown (10YR 4/6) mottling (5-15%), silt (15-30%), sand (0-5%), gravel (0-5%), very stiff, no dilatancy, low to medium toughness, medium plasticity, moist.	CL				3.25					
2 CS	120 114		9 10 11 12	9 - 23.3' **SILT:** ML, grayish brown (10YR 5/2), gray (10YR 5/1) mottling (0-5%), dark gray (10YR 4/1) mottling (0-5%), hard, no dilatancy, high toughness, low plasticity, dry.	ML				3.5 4.5					

I hereby certify that the information on this form is true and correct to the best of my knowledge.

Signature	Firm Ramboll 234 W. Florida Street, Milwaukee, WI 53204	Tel: (414) 837-3607 Fax: (414) 837-3608

SOIL BORING LOG INFORMATION SUPPLEMENT

Boring Number SB301

Sample									Soil Properties					
Number and Type	Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Compressive Strength (tsf)	Moisture Content	Liquid Limit	Plasticity Index	P 200	RQD/ Comments
			13	9 - 23.3' **SILT:** ML, grayish brown (10YR 5/2), gray (10YR 5/1) mottling (0-5%), dark gray (10YR 4/1) mottling (0-5%), hard, no dilatancy, high toughness, low plasticity, dry. *(continued)*					4.5					
			14											
			15						4.5					
			16											
			17						4.5					
			18		ML									
			19						4.5					
3 CS	120 120		20											
			21						4.5					
			22											
			23						4.5					
			24	23.3 - 24.8' **POORLY-GRADED SAND:** SP, yellowish brown (10YR 5/6), subrounded to rounded, fine sand, silt (0-5%), loose, moist to dry.	SP									
			25	24.8 - 48' **LEAN CLAY:** CL, dark gray (10YR 4/1), silt (15-30%), sand (0-5%), gravel (0-5%), hard, no dilatancy, high toughness, medium to high plasticity, dry to moist, gravel and sand increase to (5-15%) with depth.					4.5					
			26											
			27						4.5					
			28		CL									
			29						4.5					
4 CS	96 96		30											
			31						4.5					
			32											

Boring Number SB301

Sample		Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Soil Properties					RQD/ Comments
Number and Type	Length Att. & Recovered (in)								Compressive Strength (tsf)	Moisture Content	Liquid Limit	Plasticity Index	P 200	
5 CS	120 120		33 34 35 36 37 38 39 40 41 42 43 44 45 46 47	24.8 - 48' **LEAN CLAY:** CL, dark gray (10YR 4/1), silt (15-30%), sand (0-5%), gravel (0-5%), hard, no dilatancy, high toughness, medium to high plasticity, dry to moist, gravel and sand increase to (5-15%) with depth. *(continued)*	CL									
6 SH	24 20		48 49	48 - 50.						14.1	27	13	65.4	SH= Shelby Tube
7 CS	96 60		50 51 52	50 - 56.2' **SILTY CLAY:** CL/ML, grayish brown (10YR 5/2) to light olive brown (2.5Y 5/4), sand (5-15%), gravel (5-15%), hard, no dilatancy, high toughness, medium to high plasticity, dry.	CL/ML									

Boring Number SB301

Sample									Soil Properties					
Number and Type	Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Compressive Strength (tsf)	Moisture Content	Liquid Limit	Plasticity Index	P 200	RQD/ Comments
			53 54 55 56	50 - 56.2' **SILTY CLAY:** CL/ML, grayish brown (10YR 5/2) to light olive brown (2.5Y 5/4), sand (5-15%), gravel (5-15%), hard, no dilatancy, high toughness, medium to high plasticity, dry. *(continued)*	CL/ML									
			57	56.2 - 57' **POORLY-GRADED SAND:** SP, gray (10YR 5/1), rounded to subrounded, fine to medium sand, gravel (0-5%), dense, moist.	SP									
				57 - 57.4' **SILTY CLAY:** CL/ML, grayish brown (10YR 5/2) to light olive brown (2.5Y 5/4), sand (5-15%), gravel (5-15%), hard, no dilatancy, high toughness, medium to high plasticity, moist.	CL/ML									
			58	57.4 - 58' **WELL-GRADED GRAVEL WITH CLAY AND SAND:** (GW-GC)s, subangular to subrounded gravel, dense, wet.	(GW-GC)s									
8 MC	24 24		59	58 - 60.										MC= Modified California Sample
9 CS	96 96		60 61 62 63	60 - 63.8' **SILTY CLAY:** CL/ML, grayish brown (10YR 5/2) to light olive brown (2.5Y 5/4), sand (5-15%), gravel (5-15%), hard, no dilatancy, high toughness, medium to high plasticity, dry.	CL/ML									
			64 65 66	63.8 - 66.4' **WELL-GRADED SAND WITH GRAVEL:** (SW)g, dark grayish brown (10YR 4/2), subrounded sand, clay (5-15%), clay nodules (0-5%), loose, wet.	(SW)g									
			67	66.4 - 68' **SILT:** ML, dark grayish brown (10YR 4/2), gravel (0-5%), sand (0-5%), low toughness, non-plastic, moist.	ML									
10 MC	24 24		68 69	68 - 70.						13.1	23	9	68.7	
11 CS	60 60		70 71 72	70 - 87.5' **SILT:** ML, dark grayish brown (10YR 4/2), gravel (0-5%), sand (0-5%), low toughness, non-plastic, moist.	ML									

Boring Number SB301

Sample									Soil Properties					
Number and Type	Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Compressive Strength (tsf)	Moisture Content	Liquid Limit	Plasticity Index	P 200	RQD/ Comments
12 CS 13 CS	60 43 120 120		73 74 75 76 77 78 79 80 81 82 83 84 85 86 87	70 - 87.5' **SILT:** ML, dark grayish brown (10YR 4/2), gravel (0-5%), sand (0-5%), low toughness, non-plastic, moist. *(continued)*	ML									
			88	87.5 - 88.3' **SILTY SAND:** SM, dark grayish brown (10YR 4/2), dense.	SM									
			89	88.3 - 90' **SILT:** ML, dark grayish brown (10YR 4/2), gravel (0-5%), sand (0-5%), low toughness, non-plastic, moist.	ML									
14 SH	24 0		90 91 92	90 - 92.										

SOIL BORING LOG INFORMATION SUPPLEMENT

Boring Number SB301

Sample		Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Soil Properties					RQD/ Comments
Number and Type	Length Att. & Recovered (in)								Compressive Strength (tsf)	Moisture Content	Liquid Limit	Plasticity Index	P 200	
15 CS	96 96		93 94 95	92 - 95.3' **SILT:** ML, dark grayish brown (10YR 4/2), gravel (0-5%), sand (0-5%), low toughness, non-plastic, moist.	ML									
			96	95.3 - 96.8' **SANDY SILT:** s(ML), gray (10YR 5/1) to grayish brown (10YR 5/2), cohesive, high to medium toughness, non-plastic, moist.	s(ML)									
			97	96.8 - 98' **SILT:** ML, dark grayish brown (10YR 4/2), gravel (0-5%), sand (0-5%), low toughness, non-plastic, moist.	ML									
16 SH	24 24		98 99	98 - 100.						15.7	37	22	82.2	
			100	100' End of Boring.										

R000851

SOIL BORING LOG INFORMATION

Page 1 of 2

Facility/Project Name Newton Power Station	License/Permit/Monitoring Number	Boring Number XPW01

Boring Drilled By: Name of crew chief (first, last) and Firm Russ Gordon Cascade Drilling	Date Drilling Started 1/20/2021	Date Drilling Completed 1/20/2021	Drilling Method Mini Sonic

Common Well Name XPW01	Final Static Water Level Feet (NAVD88)	Surface Elevation 548.62 Feet (NAVD88)	Borehole Diameter 6.0 inches

Local Grid Origin ☐ (estimated: ☐) or Boring Location ☒

State Plane 824,975.39 N, 997,851.62 E [✓ E]/ W

1/4 of 1/4 of Section 26, T 6 N, R 8 E

Lat 38° 55' 55.93"

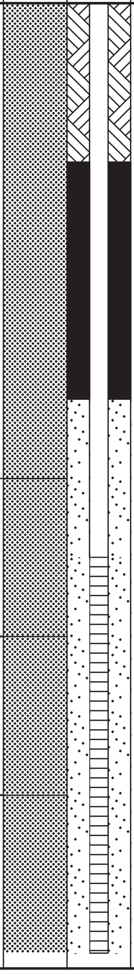
Long -88° 17' 7.87"

Local Grid Location

Feet ☐ N ☐ S

Feet ☐ E ☐ W

Facility ID	County Jasper	State IL	Civil Town/City/ or Village Newton

Sample									Soil Properties					
Number and Type	Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Compressive Strength (tsf)	Moisture Content	Liquid Limit	Plasticity Index	P 200	RQD/ Comments
1 CS	60 60		1 2 3 4	0 - 6' ASH, gray (10YR 5/1), silt sized grains, fine sand (0-5%), gravel (0-5%), dry.	(FILL) ASH									CS= Core Sample
2 CS	36 36		5	5 - 6' cobbles.	(FILL)									
			6 7	6 - 8' ASH, gray (10YR 5/1), silt sized grains, fine sand (0-5%), gravel (0-5%), dry.	(FILL) ASH									
3 MC	24 24		8 9	8 - 10' ASH, sand and silt sized grains.	(FILL) ASH				87.7	18.6	47		11.8	MC= Modified California Sample
4 CS	60 60		10 11 12	10 - 15' ASH, gray (10YR 5/1), sand with gravel sized grains, slag-like material (0-5%), wet.	(FILL) ASH									

I hereby certify that the information on this form is true and correct to the best of my knowledge.

Signature	Firm Ramboll 234 W. Florida Street, Milwaukee, WI 53204	Tel: (414) 837-3607 Fax: (414) 837-3608

SOIL BORING LOG INFORMATION SUPPLEMENT

Boring Number XPW01

Page 2 of 2

Sample									Soil Properties					
Number and Type	Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Compressive Strength (tsf)	Moisture Content	Liquid Limit	Plasticity Index	P 200	RQD/ Comments
			13 14	10 - 15' ASH, gray (10YR 5/1), sand with gravel sized grains, slag-like material (0-5%), wet. *(continued)*	(FILL) ASH									
5 MC	24 24		15 16	15 - 17' ASH, clay sized grains.	(FILL) ASH				84.4 0.5	12.6	35	18	61.3	
6 CS	36 36		17	17 - 18' **LEAN CLAY:** CL, gray (10YR 5/1), medium plasticity, orange mottling (0-5%), medium stiff, moist.	CL									
			18 19	18 - 20' **SILTY CLAY:** CL/ML, yellowish brown (10YR 5/6), subrounded fine gravel (0-5%), low plasticity, hard, moist.	CL/ML				4.5					
			20	20' End of Boring.										

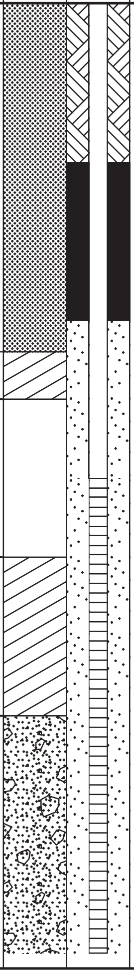
SOIL BORING LOG INFORMATION

Facility/Project Name Newton Power Station	License/Permit/Monitoring Number	Boring Number XPW02	
Boring Drilled By: Name of crew chief (first, last) and Firm Russ Gordon Cascade Drilling	Date Drilling Started 1/19/2021	Date Drilling Completed 1/19/2021	Drilling Method Mini Sonic
Common Well Name XPW02	Final Static Water Level Feet (NAVD88)	Surface Elevation 551.97 Feet (NAVD88)	Borehole Diameter 6.0 inches

Local Grid Origin ☐ (estimated: ☐) or Boring Location ☒
State Plane 825,023.53 N, 998,601.28 E [✓ E]/ W
1/4 of 1/4 of Section 26, T 6 N, R 8 E
Lat 38° 55' 56.41"
Long -88° 16' 58.38"
Local Grid Location ☐ N ☐ S Feet ☐ E ☐ W Feet

Facility ID	County Jasper	State IL	Civil Town/City/ or Village Newton

Sample: Number and Type	Sample: Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Soil Properties: Compressive Strength (tsf)	Soil Properties: Moisture Content	Soil Properties: Liquid Limit	Soil Properties: Plasticity Index	Soil Properties: P 200	RQD/ Comments
1 CS	60 60		0 - 4.4	0 - 4.4' ASH, brown (10YR 5/3), silt and sand sized grains , slag-like material (0-5%), fine to coarse gravel (0-5%), dry.	(FILL) ASH									CS= Core Sample
			4.4 - 5	4.4 - 5' **FILL, LEAN CLAY:** CL, very dark gray (10YR 3/1), gravel (0-5%), coal (0-5%), low plasticity, hard.	(FILL) CL				4					
2 MC	24 24		5 - 7	5 - 7' not analyzed.										MC= Modified California Sample
3 MC	24 24		7 - 9	7 - 9' **FILL, LEAN CLAY:** CL, very dark gray (10YR 3/1), gravel (0-5%), coal fragments (0-5%), low plasticity, hard.	(FILL) CL				92.9	29.1	36	20	54.9	
4 CS 5 CS	12 12 60 60		9 - 13.5	9 - 13.5' **FILL, WELL-GRADED SAND WITH GRAVEL:** (SW)g, brown (10YR 5/3), fine to coarse sand, fine to coarse gravel (15-25%), coal (0-5%), wet.	(FILL) (SW)g									



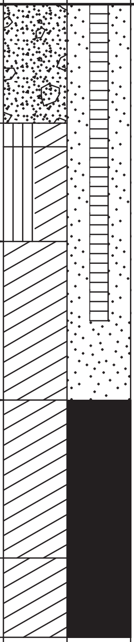
I hereby certify that the information on this form is true and correct to the best of my knowledge.

Signature

Firm Ramboll
234 W. Florida Street, Milwaukee, WI 53204
Tel: (414) 837-3607
Fax: (414) 837-3608

SOIL BORING LOG INFORMATION SUPPLEMENT

Boring Number XPW02



Sample: Number and Type	Sample: Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Soil Properties: Compressive Strength (tsf)	Soil Properties: Moisture Content	Soil Properties: Liquid Limit	Soil Properties: Plasticity Index	Soil Properties: P 200	RQD/ Comments
			13	9 - 13.5' **FILL, WELL-GRADED SAND WITH GRAVEL:** (SW)g, brown (10YR 5/3), fine to coarse sand, fine to coarse gravel (15-25%), coal (0-5%), wet. *(continued)* 12.8 - 13.8' shale fragments (20-30%).	(FILL) (SW)g									
			14	13.5 - 15' **FILL, CLAYEY SILT** ML/CL, very dark gray (10YR 3/1), organic material (15-25%), very fine to fine sand (0-5%), wet.	(FILL) ML/CL									
6 MC	24 24		15 16	15 - 17' **FILL, LEAN CLAY:** CL, very dark gray (10YR 3/1).	(FILL) CL				103.7	21.8	36	22	80.2	
7 CS	36 36		17 18	17 - 19' **LEAN CLAY:** CL, very dark gray (10YR 3/1), medium plasticity, medium stiff, moist.	CL				0.5					
			19	19 - 20' **LEAN CLAY:** CL, grayish brown (10YR 5/2), fine to coarse gravel (0-5%), low plasticity, very stiff, moist.	CL				2.5					
			20	20' End of Boring.										

SOIL BORING LOG INFORMATION

Page 1 of 2

Facility/Project Name Newton Power Station	License/Permit/Monitoring Number	Boring Number XPW03	
Boring Drilled By: Name of crew chief (first, last) and Firm Russ Gordon Cascade Drilling	Date Drilling Started 1/19/2021	Date Drilling Completed 1/19/2021	Drilling Method Mini Sonic
Common Well Name XPW03	Final Static Water Level Feet (NAVD88)	Surface Elevation 550.81 Feet (NAVD88)	Borehole Diameter 6.0 inches

Local Grid Origin ☐ (estimated: ☐) or Boring Location ☒

State Plane 824,558.16 N, 1,000,444.81 E [✓ E]/ W

1/4 of 1/4 of Section 25, T 6 N, R 8 E

Lat 38° 55' 51.8"

Long -88° 16' 35.06"

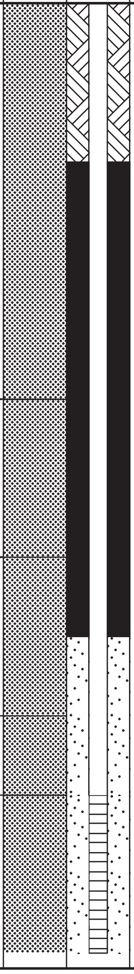
Local Grid Location

Feet ☐N ☐S

Feet ☐E ☐W

Facility ID	County	State	Civil Town/City/ or Village
	Jasper	IL	Newton

Sample: Number and Type	Sample: Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Soil Properties: Compressive Strength (tsf)	Soil Properties: Moisture Content	Soil Properties: Liquid Limit	Soil Properties: Plasticity Index	Soil Properties: P 200	RQD/ Comments
1 CS	60 60		1 2 3 4	0 - 5' ASH, gray (10YR 5/1), silt sized grains, very fine to fine sand (5-15%), slag-like material (5-10%), dry. 3.5' moist.	(FILL) ASH									CS= Core Sample
2 MC	24 24		5 6	5 - 7' ASH, sand and silt sized grains. 5.5' moist to wet.	(FILL) ASH				75.3	17.4	33	6	21.5	MC= Modified California Sample
3 CS	36 36		7 8	7 - 9' ASH, gray (10YR 5/1), silt sized grains, wet.	(FILL) ASH									
			9	9 - 10' ASH, light gray (10YR 7/1), gravel sized grains, angular, fine to coarse gravel, coarse sand (0-5%), wet.	(FILL) ASH									
4 CS	60 60		10 11 12	10 - 13.6' ASH, grayish brown (10YR 5/2), sand to gravel sized grains, fine to coarse sand, fine to coarse gravel (15-25%), coal (0-5%), wet.	(FILL) ASH									



I hereby certify that the information on this form is true and correct to the best of my knowledge.

Signature	Firm Ramboll 234 W. Florida Street, Milwaukee, WI 53204	Tel: (414) 837-3607 Fax: (414) 837-3608

SOIL BORING LOG INFORMATION SUPPLEMENT

Boring Number XPW03

Sample		Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Soil Properties					RQD/ Comments
Number and Type	Length Att. & Recovered (in)								Compressive Strength (tsf)	Moisture Content	Liquid Limit	Plasticity Index	P 200	
			13	10 - 13.6' ASH, grayish brown (10YR 5/2), sand to gravel sized grains, fine to coarse sand, fine to coarse gravel (15-25%), coal (0-5%), wet. *(continued)*	(FILL) ASH									
			14	13.6 - 14.7' ASH, gray (10YR 5/1), sand sized grains, fine to medium sand, fine to coarse gravel (0-5%), coal (0-5%), wet.	(FILL) ASH									
5 MC	24 18		15	14.7 - 15' ASH, gray (10YR 5/1), silt sized grains, very fine to fine sand (0-5%), wet.	(FILL) ASH				103.6	16.7	12		16.3	
			16	15 - 17' ASH, sand and silt sized grains.	(FILL) ASH									
6 CS	36 36		17 18	17 - 19' ASH, gray (10YR 5/1), silt sized grains, very fine to coarse sand (0-5%), fine gravel (0-5%) , wet.	(FILL) ASH									
			19	19 - 20' **SILTY CLAY:** CL/ML, yellowish brown (10YR 5/6), subrounded fine gravel (0-5%), low plasticity, very stiff, moist.	CL/ML				2					
			20	20' End of Boring.										

RAMBOLL

SOIL BORING LOG INFORMATION

Page 1 of 2

Facility/Project Name Newton Power Station	License/Permit/Monitoring Number	Boring Number XPW04

Boring Drilled By: Name of crew chief (first, last) and Firm Russ Gordon Cascade Drilling	Date Drilling Started 1/19/2021	Date Drilling Completed 1/19/2021	Drilling Method Mini Sonic
Common Well Name XPW04	Final Static Water Level Feet (NAVD88)	Surface Elevation 551.90 Feet (NAVD88)	Borehole Diameter 6.0 inches

Local Grid Origin ☐ (estimated: ☐) or Boring Location ☒

State Plane 824,130.99 N, 1,001,110.06 E [✓ E]/ W

1/4 of 1/4 of Section 25, T 6 N, R 8 E

Lat 38° 55' 47.57"

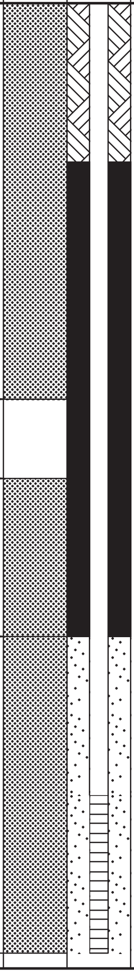
Long -88° 16' 26.64"

Local Grid Location

Feet ☐ N ☐ S

Feet ☐ E ☐ W

Facility ID	County Jasper	State IL	Civil Town/City/ or Village Newton



Sample									Soil Properties					
Number and Type	Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Compressive Strength (tsf)	Moisture Content	Liquid Limit	Plasticity Index	P 200	RQD/ Comments
1 CS	60 60		0	0 - 5' ASH, gray (10YR 5/1), silt sized grains, very fine to fine sand (0-5%), fine to coarse gravel (0-5%), dry.	(FILL) ASH									CS= Core Sample
2 MC	12 4		5	5 - 6.										MC= Modified California Sample, 4" of concrete recovered in MC
3 MC	24 24		6	6 - 8' ASH, sand and silt sized grains. 7' moist.	(FILL) ASH				73.9	31.1	41	3	13.9	
4 CS	24 24		8	8 - 12' ASH, gray (10YR 5/1), silt sized grains, very fine to fine sand (0-5%), fine to coarse gravel (0-5%), moist.	(FILL) ASH									
5 CS	60 60		10											
			12											

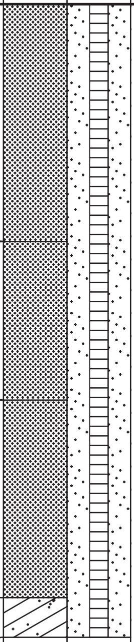
I hereby certify that the information on this form is true and correct to the best of my knowledge.

Signature	Firm Ramboll 234 W. Florida Street, Milwaukee, WI 53204	Tel: (414) 837-3607 Fax: (414) 837-3608

SOIL BORING LOG INFORMATION SUPPLEMENT

Boring Number XPW04

Page 2 of 2



Sample									Soil Properties					
Number and Type	Length Att. & Recovered (in)	Blow Counts	Depth In Feet	Soil/Rock Description And Geologic Origin For Each Major Unit	U S C S	Graphic Log	Well Diagram	PID 10.6 eV Lamp	Compressive Strength (tsf)	Moisture Content	Liquid Limit	Plasticity Index	P 200	RQD/ Comments
			13 14	12 - 15' ASH, gray (10YR 5/1), sand to gravel sized grains, very fine to fine sand (0-5%), fine to coarse gravel (0-5%), moist. 12.5' wet.	(FILL) ASH									
6 MC	24 24		15 16	15 - 17' ASH, sand and silt sized grains.	(FILL) ASH				80.8	31.1	46	4	33.3	
7 CS	36 36		17 18 19	17 - 19.5' ASH, gray (10YR 5/1), sand to gravel sized grains, very fine to fine sand (0-5%), fine to coarse gravel (0-5%), wet.	(FILL) ASH									
			20	19.5 - 20' **LEAN CLAY WITH SAND:** (CL)s, brown (10YR 5/3), fine to medium sand (15-25%), fine gravel (0-5%), wet. 20' End of Boring.	(CL)s									

Surface Elevation: **529.93**

Datum **msl**

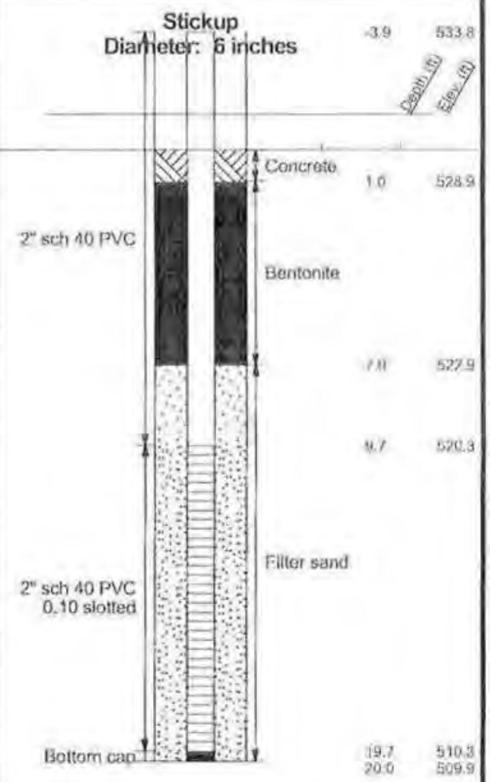
Completion Date: **6/19/10**

Northing: **822688.04**

Easting: **995465.25**

DEPTH IN FEET	DESCRIPTION OF MATERIAL	GRAPHIC LOG	DRY UNIT WEIGHT (pcf) SPT BLOW COUNTS CORE RECOVERY/RQD	SAMPLES
0	Soft, brown, silty CLAY - CL			
5	Stiff, brown, sandy CLAY - CL			
	Hard, brown, sandy CLAY with gravel - CL ▽			
10				
	Hard, dark gray CLAY and glacial till - CH			
15				
20	Boring terminated at 20 feet.			
25				
30				
35				

WELL DIAGRAM



NOTE: STRATIFICATION LINES REPRESENT THE APPROXIMATE BOUNDARIES BETWEEN SOIL TYPES AND THE TRANSITION MAY BE GRADUAL. GRAPHIC LOG FOR ILLUSTRATION PURPOSES ONLY.

LOG OF BORING 2002 WL J017150.01ENV - AMEREN-NEWTON.GPJ GTINC 0538301.GPJ 12/22/10

GROUNDWATER DATA

ENCOUNTERED AT 8.5 FEET ▽

DRILLING DATA

4 1/4" AUGER ___ HOLLOW STEM

WASHBORING FROM ___ FEET

MVU DRILLER KCR LOGGER

CME 750X DRILL RIG

HAMMER TYPE Auto

REMARKS:

Drawn by: KA	Checked by: RBP	App'vd by: DTK
Date: 6/29/10	Date: 2-7-11	Date: 2-7-11

GEOTECHNOLOGY INC
FROM THE GROUND UP

Ameren Power Plant
Newton, Illinois

LOG OF BORING: APW-2

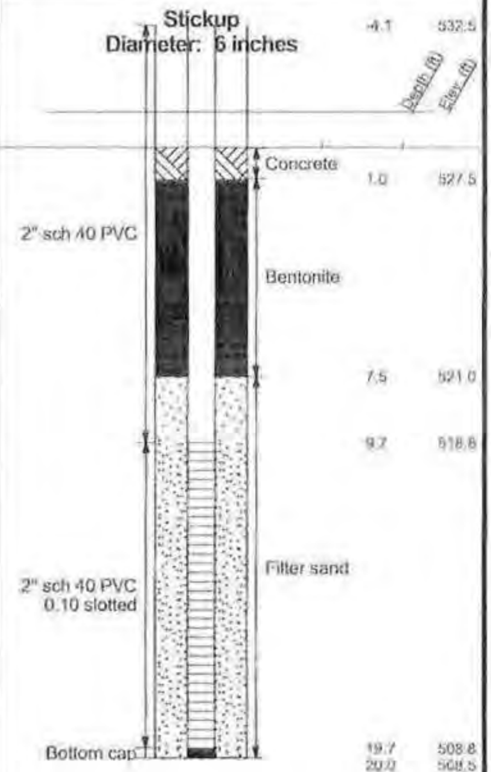
Project No. J017150.01

Surface Elevation: 528.47
Datum msl

Completion Date: 6/18/10
Northing: 821379.76
Easting: 998975.74

DEPTH IN FEET	DESCRIPTION OF MATERIAL	GRAPHIC LOG	DRY UNIT WEIGHT (pcf) SPT BLOW COUNTS CORE RECOVERY/ROD	SAMPLES
0	Soft, brown, silty CLAY - CL	▨		
6	Soft, brown, sandy CLAY with gravel - CL	▨		
9	Hard, brown, sandy CLAY with gravel - CL	▨		
13	Hard, brownish-gray, sandy CLAY with gravel - CL	▨		
20	Boring terminated at 20 feet.			

WELL DIAGRAM



NOTE: STRATIFICATION LINES REPRESENT THE APPROXIMATE BOUNDARIES BETWEEN SOIL TYPES. THE TRANSITION MAY BE GRADUAL. GRAPHIC LOG FOR ILLUSTRATION PURPOSES ONLY

GROUNDWATER DATA

X FREE WATER NOT ENCOUNTERED DURING DRILLING

DRILLING DATA

4 1/4" AUGER ___ HOLLOW STEM
WASHBORING FROM ___ FEET
MVU DRILLER KCR LOGGER
CME 750X DRILL RIG
HAMMER TYPE Auto

REMARKS:

Drawn by: KA	Checked by: RSR	App'vd. by: DTK
Date: 6/29/10	Date: 2/7/11	Date: 2-7-11

GEOTECHNOLOGY INC
FROM THE GROUND UP

Ameren Power Plant
Newton, Illinois

LOG OF BORING: APW-3

Project No. J017150.01

Surface Elevation: 521.56

Datum msl

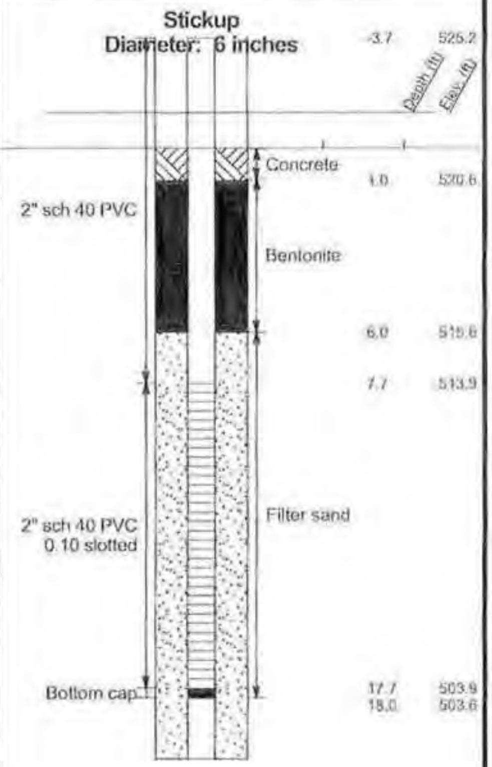
Completion Date: 6/19/10

Northing 823246.45

Easting: 1001379.56

DEPTH IN FEET	DESCRIPTION OF MATERIAL	GRAPHIC LOG	DRY UNIT WEIGHT (pcf) SPT BLOW COUNTS CORE RECOVERY/RQD	SAMPLES
	Soft, brown, silty CLAY - CL	▨		
5				
	Soft, brown, sandy CLAY - CL ∇	▨		
10				
	Stiff, brown, sandy CLAY with gravel - CL	▨		
15				
	Boring terminated at 18 feet.			
20				
25				
30				
35				

WELL DIAGRAM



NOTE: STRATIFICATION LINES REPRESENT THE APPROXIMATE BOUNDARIES BETWEEN SOIL TYPES AND THE TRANSITION MAY BE GRADUAL. GRAPHIC LOG FOR ILLUSTRATION PURPOSES ONLY.

LOG OF BORING 2002 WL J017150.01ENV - AMEREN-NEWTON.GPJ GTINC 0638301.GPJ 2/7/11

GROUNDWATER DATA

ENCOUNTERED AT 8 FEET ∇

DRILLING DATA

4 1/4" AUGER __ HOLLOW STEM

WASHBORING FROM __ FEET

MVU DRILLER KCR LOGGER

CME 750X DRILL RIG

HAMMER TYPE Auto

REMARKS:

Drawn by: KA	Checked by: RJS	App'vd. by: DRK
Date: 6/29/10	Date: 2-7-11	Date: 2-7-11

GEOTECHNOLOGY INC
FROM THE GROUND UP

Ameren Power Plant
Newton, Illinois

LOG OF BORING: APW-4

Project No. J017150.01

FIELD BORING LOG

HANSON

CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 10/22/2015
Finish: 10/22/2015
WEATHER: Sunny, breezy, warm, lo-80s

CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550X ATV Drill
Drilling Method: 4¼" HSA, macro-core sampler, split spoon sampler
FIELD STAFF: Driller: C. Dutton
Helper: C. Jones
Eng/Geo: S. Keim

BOREHOLE ID: APW5
Well ID: APW5
Surface Elev: 541.57 ft. MSL
Completion: 68.00 ft. BGS
Station: 7,758.02N
9,318.19E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 26, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = 58.00 - During Drilling
▼ =
▽ =

Number	Recov / Total (in) *% Recovery*	Type	*Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft³)	Qu (tsf) *Qp (tsf)* Failure Type
1A	60/60 *100%*	DP		7		*3.00*
1B				13		*2.50*
2A	60/60 *100%*	DP		25		*3.25*
2B				22		*2.25*
3A	60/60 *100%*	DP		19		*1.50*
3B				19		*3.00*
4A	36/36 *100%*	DP		9		*2.00*
5A	23/24 *96%*	SS	*14-28* *40-50* N=68	9		*4.50*

Depth ft. BGS: 2, 4, 6, 8, 10, 12, 14, 16, 18, 20

Lithologic Description

Very dark grayish brown (10YR3/2), dry, very stiff, SILT with little clay and trace very fine- to medium-grained sand, roots.

Yellowish brown (10YR5/6), dry, very stiff, SILT with little clay and few very fine- to medium-grained sand.

Yellowish brown (10YR5/6) with 10% gray (10YR6/1) mottles, moist, very stiff, silty CLAY with few very fine- to medium-grained sand and trace small gravel.

Gray (10YR5/1) with 20% dark yellowish brown (10YR4/6) mottles, moist, very stiff, CLAY with some silt, trace very fine- to fine-grained sand.

Dark grayish brown (10YR4/2), moist, stiff, CLAY with little silt and trace very fine- to fine-grained sand.

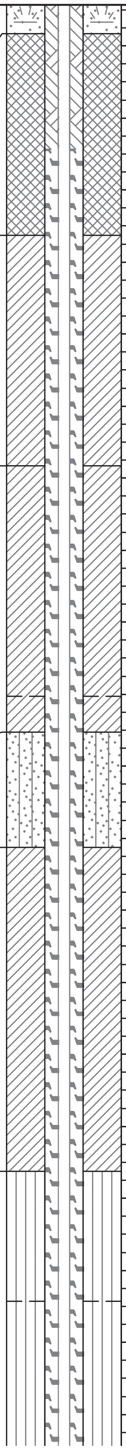
Gray (10YR6/1), moist, medium dense, very fine- to fine-grained SAND and SILT with little clay.

Gray (10YR5/1) with 5% yellowish brown (10YR5/6) mottles, moist, very stiff, silty CLAY with few fine- to coarse-grained sand and trace small gravel.

Yellowish brown (10YR5/6) with 15% grayish brown (10YR5/2) mottles, moist, stiff, SILT with little clay and trace fine- to coarse-grained sand and small gravel.

Brown (10YR5/3), moist, hard, SILT with little clay, few very fine- to coarse-grained sand, and trace small gravel.

Borehole Detail



Elevation ft. MSL: 540, 538, 536, 534, 532, 530, 528, 526, 524, 522

Remarks

NOTE(S): APW5 installed in borehole.

FIELD BORING LOG

HANSON

CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 10/22/2015
Finish: 10/22/2015
WEATHER: Sunny, breezy, warm, lo-80s

CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550X ATV Drill
Drilling Method: 4¼" HSA, macro-core sampler, split spoon sampler
FIELD STAFF: Driller: C. Dutton
Helper: C. Jones
Eng/Geo: S. Keim

BOREHOLE ID: APW5
Well ID: APW5
Surface Elev: 541.57 ft. MSL
Completion: 68.00 ft. BGS
Station: 7,758.02N
9,318.19E

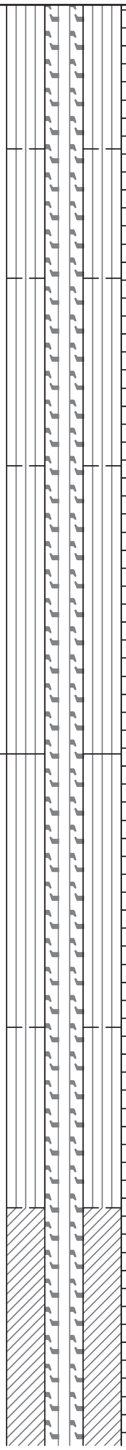
TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 26, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = 58.00 - During Drilling
▼ =
▽ =

SAMPLE			TESTING			
Number	Recov / Total (in) *% Recovery*	Type	*Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft^3)	Qu (tsf) *Qp (tsf)* Failure Type
6A	21/24 *88%*	SS	*11-26* *21-14* N=47	9		*4.50*
7A	24/24 *100%*	SS	*5-5* *8-13* N=13	16		*4.25*
8A	22/24 *92%*	SS	*18-31* *43-27* N=74	9		*4.50*
9A	21/24 *88%*	SS	*4-5* *11-11* N=16	14		*2.75*
10A	22/24 *92%*	SS	*3-6* *9-12* N=15	15		*3.75*
11A	24/24 *100%*	SS	*4-7* *13-16* N=20	14		*4.50*
12A	24/24 *100%*	SS	*4-7* *11-17* N=18	16		*4.50*
13A	24/24 *100%*	SS	*5-9* *12-15* N=21	18		*4.50*
14A	24/24 *100%*	SS	*4-8* *11-14* N=19	16		*4.50*
15A	24/24 *100%*	SS	*5-13* *16-23* N=29	12		*4.50*

Depth ft. BGS	Lithologic Description	Elevation ft. MSL
	Brown (10YR5/3), moist, hard, SILT with little clay, few very fine- to coarse-grained sand, and trace small gravel. *[Continued from previous page]*	520
22	Brown (10YR5/3) with 5% gray (10YR6/1) and 5% yellowish brown (10YR5/6) mottles, moist, hard, SILT with some clay and trace very fine- to fine-grained sand and small gravel.	518
24	Brown (10YR5/3), moist, hard, SILT with little clay, few very fine- to coarse-grained sand, and trace small gravel.	516
26		514
28	Brown (10YR5/3) with 5% gray (10YR6/1) and 5% yellowish brown (10YR5/6) mottles, moist, hard, SILT with some clay and trace very fine- to fine-grained sand and small gravel.	512
30		
32	Dark gray (10YR4/1), moist, hard, SILT with some clay, few very fine- to coarse-grained sand and trace small gravel.	510
34		508
36	Light olive brown (2.5Y5/3) with 5% gray (10YR5/1) mottles, moist, hard, SILT with little clay and trace very fine- to medium-grained sand.	506
38	Olive brown (2.5Y4/3) with 10% gray (N6/1) mottles, moist, hard, silty CLAY with little fine- to coarse-grained sand and trace small gravel.	504
40		502

Borehole Detail



Remarks

NOTE(S): APW5 installed in borehole.

FIELD BORING LOG

HANSON

CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 10/22/2015
Finish: 10/22/2015
WEATHER: Sunny, breezy, warm, lo-80s

CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550X ATV Drill
Drilling Method: 4¼" HSA, macro-core sampler, split spoon sampler
FIELD STAFF: Driller: C. Dutton
Helper: C. Jones
Eng/Geo: S. Keim

BOREHOLE ID: APW5
Well ID: APW5
Surface Elev: 541.57 ft. MSL
Completion: 68.00 ft. BGS
Station: 7,758.02N
9,318.19E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 26, **Tier** 6N; **Range** 8E

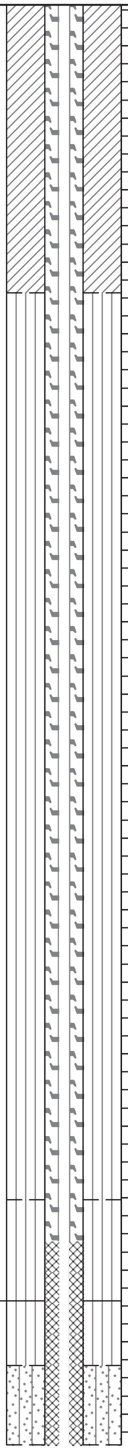
WATER LEVEL INFORMATION:
▼ = 58.00 - During Drilling
▼ =
▽ =

SAMPLE			TESTING			
Number	Recov / Total (in) *% Recovery*	Type	*Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft^3)	Qu (tsf) *Qp (tsf)* Failure Type
16A	24/24 *100%*	SS	*6-13 16-30* N=29	12		*4.50*
17A	24/24 *100%*	SS	*5-10 13-22* N=23	15		*4.50*
18A	24/24 *100%*	SS	*7-13 17-25* N=30	13		*4.50*
19A	24/24 *100%*	SS	*6-13 20-28* N=33	13		*4.50*
20A	24/24 *100%*	SS	*5-10 16-21* N=26	13		*4.50*
21A	24/24 *100%*	SS	*6-10 18-21* N=28	13		*4.50*
22A	24/24 *100%*	SS	*7-14 19-26* N=33	13		*4.50*
23A	24/24 *100%*	SS	*6-10 17-24* N=27	13		*4.50*
24A	24/24 *100%*	SS	*12-16 28-36* N=44	11		*4.50*
25A	24/24 *100%*	SS	*2-6 12-15* N=18	23		
25B				15		

Depth ft. BGS	Lithologic Description
to 44	Olive brown (2.5Y4/3) with 10% gray (N6/1) mottles, moist, hard, silty CLAY with little fine- to coarse-grained sand and trace small gravel. *[Continued from previous page]*
44	Olive brown (2.5Y4/3) with 10% gray (N6/1) mottles, moist, hard, SILT with little clay, few very fine- to coarse-grained sand and trace small gravel.
	Olive gray (5Y5/2) with 40% olive brown (2.5Y4/4) mottles, moist, hard, SILT with little clay, few very fine- to coarse-grained sand and trace small gravel.
▼ 58	Greenish gray (10G5/1) with 40% olive gray (5Y4/2) mottles, moist, medium dense, SILT with few clay and trace very fine- to fine-grained sand.
	Very dark gray (10YR3/1), wet, medium dense, very fine- to coarse-grained SAND with few silt.
60	

Depth ft. BGS: 42, 44, 46, 48, 50, 52, 54, 56, 58, 60

Borehole Detail



Elevation ft. MSL: 500, 498, 496, 494, 492, 490, 488, 486, 484, 482

Remarks

NOTE(S): APW5 installed in borehole.

FIELD BORING LOG

HANSON

CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 10/22/2015
Finish: 10/22/2015
WEATHER: Sunny, breezy, warm, lo-80s

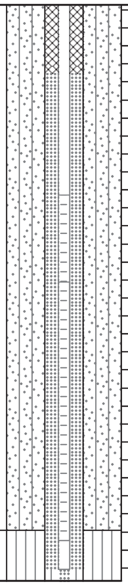
CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550X ATV Drill
Drilling Method: 4¼" HSA, macro-core sampler, split spoon sampler
FIELD STAFF: Driller: C. Dutton
Helper: C. Jones
Eng/Geo: S. Keim

BOREHOLE ID: APW5
Well ID: APW5
Surface Elev: 541.57 ft. MSL
Completion: 68.00 ft. BGS
Station: 7,758.02N
9,318.19E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 26, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = 58.00 - During Drilling
▼ =
▽ =

SAMPLE			TESTING								
Number	Recov / Total (in) *% Recovery*	Type	*Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft³)	Qu (tsf) *Qp (tsf)* Failure Type	Depth ft. BGS	Lithologic Description	Borehole Detail	Elevation ft. MSL	Remarks
26A	19/24 *79%*	SS	*3-19* *34-48* N=53	13				Very dark gray (10YR3/1), wet, very dense, very fine- to coarse-grained SAND with few silt.		480	
27A	20/24 *83%*	SS	*22-38* *33-34* N=71	16			62			478	
28A	22/24 *92%*	SS	*18-28* *31-33* N=59	14			64			476	
29A	24/24 *100%*	SS	*21-27* *24-23* N=51	16			66				
29B				14		*4.50*	68	Dark gray (10YR4/1), moist, hard, SILT with little clay and few very fine- to coarse-grained sand.		474	



End of boring = 68.0 feet

NOTE(S): APW5 installed in borehole.

FIELD BORING LOG

HANSON

CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 10/20/2015
Finish: 10/21/2015
WEATHER: Sunny, breezy, warm, lo-80s

CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550X ATV Drill
Drilling Method: 4¼" HSA, macro-core sampler, split spoon sampler
FIELD STAFF: Driller: C. Dutton
Helper: C. Jones
Eng/Geo: S. Keim

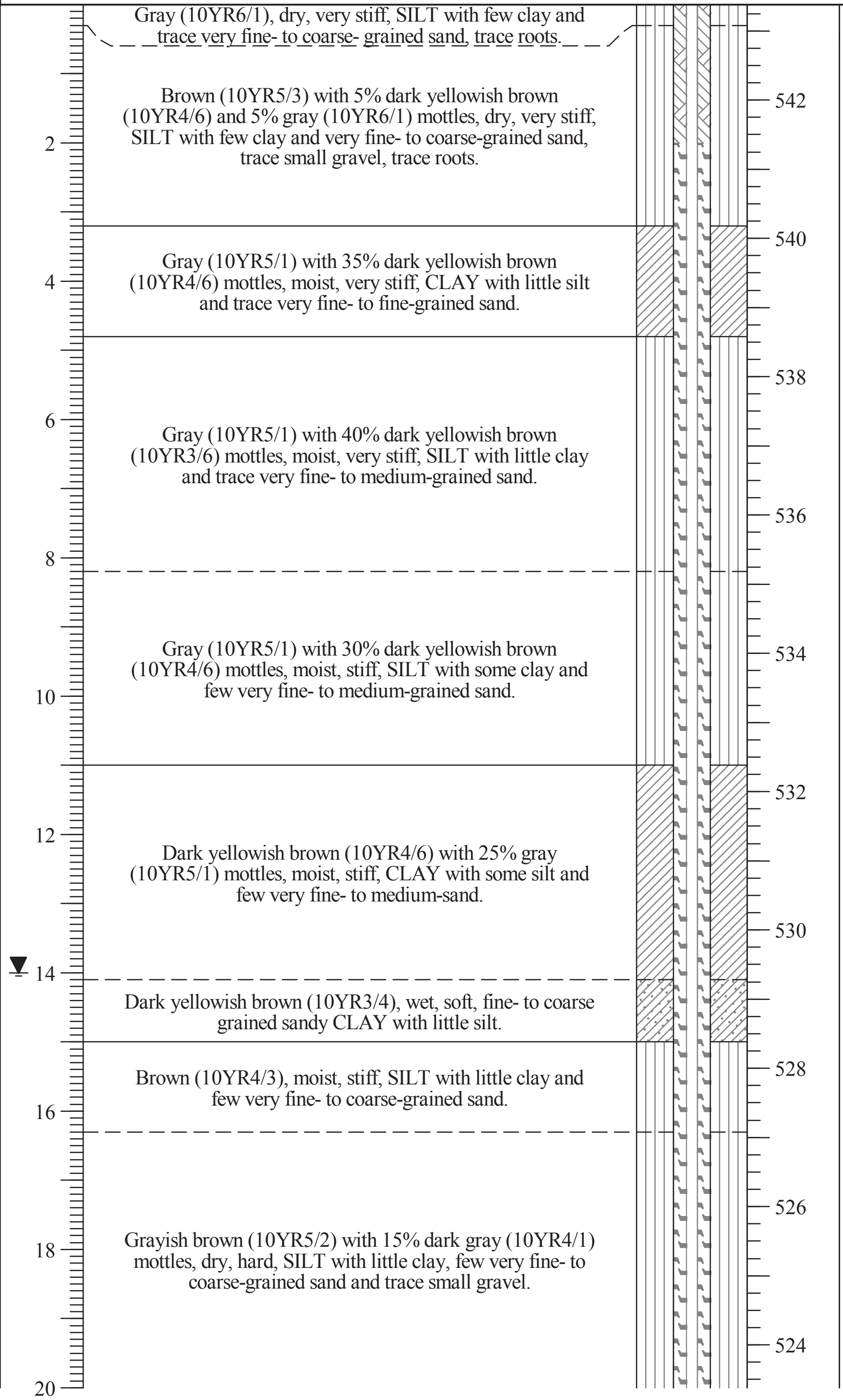
BOREHOLE ID: APW6
Well ID: APW6
Surface Elev: 543.38 ft. MSL
Completion: 74.00 ft. BGS
Station: 7,688.54N
7,811.93E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 26, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = 14.00 - During Drilling
▼ =
▽ =

SAMPLE			TESTING			
Number	Recov / Total (in) *% Recovery*	Type	*Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft³)	Qu (tsf) *Qp (tsf)* Failure Type
1A	60/60 *100%*	DP		15		*4.00*
1B				26		*3.00*
2A	60/60 *100%*	DP		18		*2.50*
2B				18		*1.00*
3A	60/60 *100%*	DP		27		*1.50*
3B				21		*1.50*
4A	12/12 *100%*	DP		10		
5A	22/24 *92%*	SS	*15-29* *41-50* N=70	8		*4.50*
6A	21/24 *88%*	SS	*14-30* *40-50* N=70	8		*4.50*

Depth ft. BGS — Lithologic Description — Borehole Detail — Elevation ft. MSL — Remarks



Gray (10YR6/1), dry, very stiff, SILT with few clay and trace very fine- to coarse- grained sand, trace roots.

Brown (10YR5/3) with 5% dark yellowish brown (10YR4/6) and 5% gray (10YR6/1) mottles, dry, very stiff, SILT with few clay and very fine- to coarse-grained sand, trace small gravel, trace roots.

Gray (10YR5/1) with 35% dark yellowish brown (10YR4/6) mottles, moist, very stiff, CLAY with little silt and trace very fine- to fine-grained sand.

Gray (10YR5/1) with 40% dark yellowish brown (10YR3/6) mottles, moist, very stiff, SILT with little clay and trace very fine- to medium-grained sand.

Gray (10YR5/1) with 30% dark yellowish brown (10YR4/6) mottles, moist, stiff, SILT with some clay and few very fine- to medium-grained sand.

Dark yellowish brown (10YR4/6) with 25% gray (10YR5/1) mottles, moist, stiff, CLAY with some silt and few very fine- to medium-sand.

Dark yellowish brown (10YR3/4), wet, soft, fine- to coarse grained sandy CLAY with little silt.

Brown (10YR4/3), moist, stiff, SILT with little clay and few very fine- to coarse-grained sand.

Grayish brown (10YR5/2) with 15% dark gray (10YR4/1) mottles, dry, hard, SILT with little clay, few very fine- to coarse-grained sand and trace small gravel.

NOTE(S): APW6 installed in borehole.

FIELD BORING LOG

HANSON

CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 10/20/2015
Finish: 10/21/2015
WEATHER: Sunny, breezy, warm, lo-80s

CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550X ATV Drill
Drilling Method: 4¼" HSA, macro-core sampler, split spoon sampler
FIELD STAFF: Driller: C. Dutton
Helper: C. Jones
Eng/Geo: S. Keim

BOREHOLE ID: APW6
Well ID: APW6
Surface Elev: 543.38 ft. MSL
Completion: 74.00 ft. BGS
Station: 7,688.54N
7,811.93E

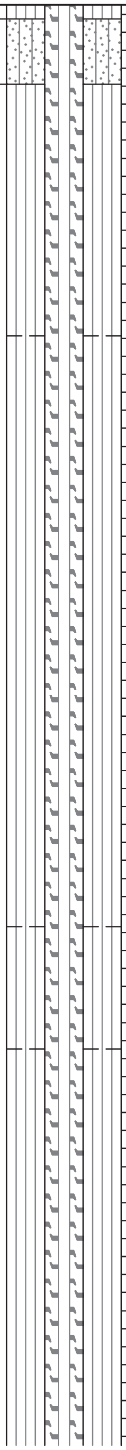
TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 26, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = 14.00 - During Drilling
▼ =
▽ =

SAMPLE			TESTING			
Number	Recov / Total (in) *% Recovery*	Type	*Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft³)	Qu (tsf) *Qp (tsf)* Failure Type
7A	15/17 *88%*	SS	*16-46* *50/5"*	9		*4.50*
8A	12/24 *50%*	SS	*14-37* *45-50* N=82	7		*4.50*
9A	24/24 *100%*	SS	*8-17* *23-32* N=40	10		*4.50*
10A	24/24 *100%*	SS	*10-22* *26-36* N=48	11		*4.50*
11A	24/24 *100%*	SS	*10-18* *23-26* N=41	10		*4.50*
12A	24/24 *100%*	SS	*6-13* *17-23* N=30	13		*4.50*
13A	24/24 *100%*	SS	*5-7* *12-19* N=19	17		*4.50*
14A	24/24 *100%*	SS	*5-9* *13-19* N=22	16		*4.50*
15A	24/24 *100%*	SS	*5-10* *15-22* N=25	15		*4.50*
16A	24/24 *100%*	SS	*5-9* *15-22* N=24	15		*4.50*

Depth ft. BGS	Lithologic Description	Elevation ft. MSL	Remarks
	Brown (10YR5/3), moist, very dense, silty, very fine- to medium-grained SAND with trace small gravel.		
		522	
22			
	Brown (10YR5/3), dry, hard, SILT with little clay and few very fine- to coarse-grained sand.		
		520	
24			
		518	
26			
		516	
28			
	Dark gray (10YR4/1), moist, hard, SILT with little clay, few very fine- to coarse-grained sand and trace small gravel.		
		514	
30			
		512	
32			
	Dark gray (10YR4/1) with 30% dark greenish gray (10Y4/1) mottles, moist, hard, SILT with some clay, few very fine- to coarse-grained sand and trace small gravel.	510	
34			
		508	
36			
	Dark gray (10YR4/1), moist, hard, SILT with little clay, few very fine- to coarse-grained sand and trace small to large gravel.	506	
38			
		504	
40			

Borehole Detail



NOTE(S): APW6 installed in borehole.

FIELD BORING LOG

CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 10/20/2015
Finish: 10/21/2015
WEATHER: Sunny, breezy, warm, lo-80s

CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550X ATV Drill
Drilling Method: 4¼" HSA, macro-core sampler, split spoon sampler
FIELD STAFF: Driller: C. Dutton
Helper: C. Jones
Eng/Geo: S. Keim

HANSON
BOREHOLE ID: APW6
Well ID: APW6
Surface Elev: 543.38 ft. MSL
Completion: 74.00 ft. BGS
Station: 7,688.54N
7,811.93E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 26, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = 14.00 - During Drilling
▼ =
▽ =

SAMPLE Number	SAMPLE Recov / Total (in) *% Recovery*	SAMPLE Type	TESTING *Blows / 6 in* N - Value **RQD**	TESTING Moisture (%)	TESTING Dry Den. (lb/ft³)	TESTING Qu (tsf) *Qp (tsf)* Failure Type
17A	21/24 *88%*	SS	*4-14 18-25* N=32	12		*4.25*
18A	24/24 *100%*	SS	*8-12 16-22* N=28	15		*4.50*
19A	22/24 *92%*	SS	*7-11 15-18* N=26	16		*4.25*
20A	22/24 *92%*	SS	*7-16 26-45* N=42	13		*4.50*
21A	21/24 *88%*	SS	*11-19 30-37* N=49	13		*4.50*
22A	19/24 *79%*	SS	*5-13 26-38* N=39	14		
23A	24/24 *100%*	SS	*12-18 29-40* N=47	13		*4.50*
24A	24/24 *100%*	SS	*7-18 30-37* N=48	13		
25A	24/24 *100%*	SS	*11-18 27-38* N=45	14		*4.50*
26A	24/24 *100%*	SS	*10-15 23-33* N=38	17		*4.50*

Depth ft. BGS: 42, 44, 46, 48, 50, 52, 54, 56, 58, 60
Elevation ft. MSL: 502, 500, 498, 496, 494, 492, 490, 488, 486, 484

Lithologic Description:

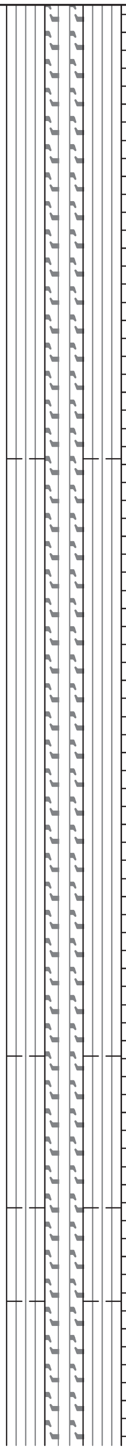
Dark gray (10YR4/1), moist, hard, SILT with little clay, few very fine- to coarse-grained sand and trace small to large gravel.
[Continued from previous page]

Olive gray (5Y4/2) with 20% dark gray (10YR4/1) mottles, moist, hard, SILT with little clay and trace very fine- to coarse- grained sand and small gravel.

Dark gray brown (2.5Y4/2) with 15% dark gray (10YR4/1) mottles, moist, hard, SILT with little clay and trace very fine- to coarse-grained sand.

Olive brown (2.5Y4/3) with 5% gray (N6/1) mottles, moist, hard, SILT with little clay and trace very fine- to medium-grained sand.

Olive brown (2.5Y4/3) with 5% gray (N6/1) mottles, moist, hard, SILT with little clay and trace very fine- to coarse-grained sand and small gravel.

Borehole Detail


Remarks

NOTE(S): APW6 installed in borehole.

FIELD BORING LOG

CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 10/20/2015
Finish: 10/21/2015
WEATHER: Sunny, breezy, warm, lo-80s

CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550X ATV Drill
Drilling Method: 4¼" HSA, macro-core sampler, split spoon sampler
FIELD STAFF: Driller: C. Dutton
Helper: C. Jones
Eng/Geo: S. Keim

BOREHOLE ID: APW6
Well ID: APW6
Surface Elev: 543.38 ft. MSL
Completion: 74.00 ft. BGS
Station: 7,688.54N
7,811.93E

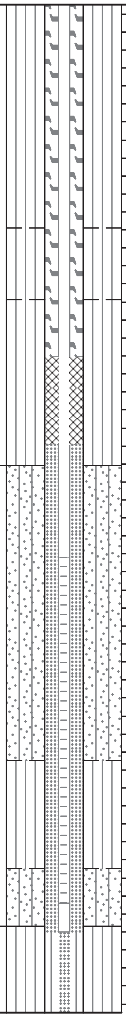
TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 26, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = 14.00 - During Drilling
▼ =
▽ =

SAMPLE			TESTING			
Number	Recov / Total (in) *% Recovery*	Type	*Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft³)	Qu (tsf) *Qp (tsf)* Failure Type
27A	24/24 *100%*	SS	*5-4* *21-32* N=25	13		*4.50*
28A	24/24 *100%*	SS	*7-18* *23-31* N=41	12		*4.50*
29A	24/24 *100%*	SS	*7-14* *18-30* N=32	13		*4.25*
30A	24/24 *100%*	SS	*13-21* *33-33* N=54	14		
31A	16/23 *70%*	SS	*3-27* *49-50/5"* N=76	13		
32A	20/23 *87%*	SS	*6-29* *38-50/5"* N=67	22		
33A	20/24 *83%*	SS	*26-28* *34-37* N=62	12		*4.50*

Depth ft. BGS	Lithologic Description	Elevation ft. MSL	Remarks
62	Olive brown (2.5Y4/3) with 5% gray (N6/1) mottles, moist, hard, SILT with little clay and trace very fine- to coarse-grained sand and small gravel. *[Continued from previous page]*	482	
64	Dark gray (10YR4/1) with 5% dark olive brown (2.5Y3/3) mottles, moist, hard, SILT with little clay and trace very fine- to coarse-grained sand and small gravel.	480	
66	Dark gray (10YR4/1), moist, hard, SILT with little clay and trace very fine- to coarse-grained sand and small gravel.	478	
68 70	Dark gray (10YR4/1), wet, very dense, silty, very fine- to coarse-grained SAND with trace small gravel.	476 474	
72	Gray (10YR5/1), wet, very dense, SILT with few very fine- to fine-grained sand.	472	
	Dark gray (10YR4/1), wet, very dense, silty, very fine- to medium-grained SAND with trace small gravel.		
74	Dark gray (10YR4/1), moist, hard, SILT with little clay and few very fine- to coarse-grained sand.	470	

Borehole Detail



End of boring = 74.0 feet

NOTE(S): APW6 installed in borehole.

FIELD BORING LOG

HANSON

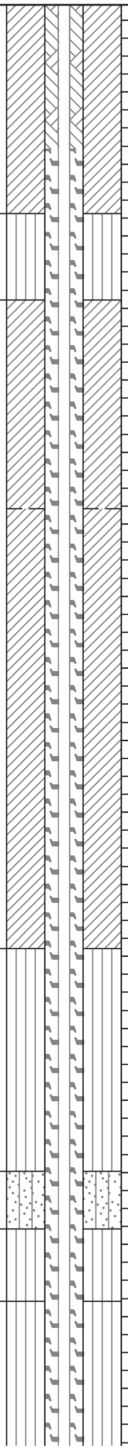
CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 11/3/2015
Finish: 11/5/2015
WEATHER: Sunny, warm, lo-70s

CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550X ATV Drill
Drilling Method: 4¼" HSA
FIELD STAFF: Driller: J. Gates
Helper: C. Clines
Eng/Geo: R. Hasenyager

BOREHOLE ID: APW7a
Well ID: APW7
Surface Elev: 536.21 ft. MSL
Completion: 83.10 ft. BGS
Station: 5,688.85N
6,151.60E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 26, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = Dry - During Drilling
▼ =
▽ =



SAMPLE: Number	SAMPLE: Recov / Total (in) *% Recovery*	SAMPLE: Type	TESTING: *Blows / 6 in* N - Value **RQD**	TESTING: Moisture (%)	TESTING: Dry Den. (lb/ft³)	TESTING: Qu (tsf) *Qp* (tsf) Failure Type	Depth ft. BGS	Lithologic Description	Elevation ft. MSL	Remarks
							2	Yellowish brown (10YR5/6), moist, medium, CLAY with some silt and trace very fine- to fine-grained sand, roots.	536 534	
							4	Light gray (10YR7/2), moist, medium, SILT with few very fine-grained sand and trace roots.		
							6	Gray (10YR5/1) with 30% yellowish brown (10YR5/8) mottles, moist, medium, CLAY with some silt, trace very fine-grained sand, and trace roots.	532 530	
							8 10 12	Gray (10YR5/1) with 30% yellowish brown (10YR5/8) mottles, moist, medium, CLAY with some silt and trace very fine- to medium-grained sand, trace small gravel, and trace roots.	528 526 524	
							14 16	Yellowish brown (10YR5/4), moist, hard, SILT with few clay, little very fine- to coarse-grained sand, and trace small to medium gravel.	522	
								Yellowish brown (10YR5/6), wet, dense, fine- to coarse-grained SAND with little silt.	520	
								Gray (10YR5/1), moist, hard, SILT with few clay, little very fine- to very coarse-grained sand, and trace small to medium gravel.		
							18 20	Yellowish brown (10YR5/6) with 20% gray (10YR5/1) mottles, dry, hard, SILT with few clay, little very fine- to very coarse-grained sand, and trace small to medium gravel.	518	

NOTE(S): APW7 installed in borehole.

FIELD BORING LOG

HANSON

CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 11/3/2015
Finish: 11/5/2015
WEATHER: Sunny, warm, lo-70s

CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550X ATV Drill
Drilling Method: 4¼" HSA
FIELD STAFF: Driller: J. Gates
Helper: C. Clines
Eng/Geo: R. Hasenyager

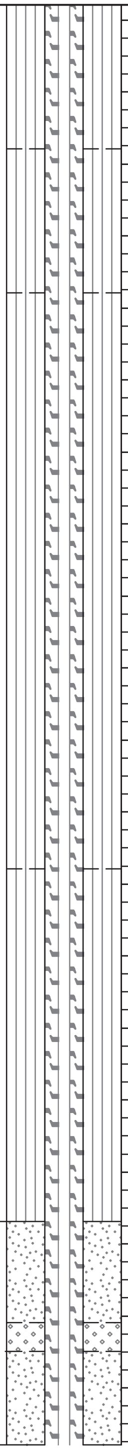
BOREHOLE ID: APW7a
Well ID: APW7
Surface Elev: 536.21 ft. MSL
Completion: 83.10 ft. BGS
Station: 5,688.85N
6,151.60E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 26, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = Dry - During Drilling
▼ =
▽ =

SAMPLE: Number	SAMPLE: Recov / Total (in) *% Recovery*	SAMPLE: Type	TESTING: *Blows / 6 in* N - Value **RQD**	TESTING: Moisture (%)	TESTING: Dry Den. (lb/ft³)	TESTING: Qu (tsf) *Qp* (tsf) Failure Type	Depth ft. BGS	Lithologic Description	Elevation ft. MSL	Remarks
								Yellowish brown (10YR5/6) with 20% gray (10YR5/1) mottles, dry, hard, SILT with few clay, little very fine- to very coarse-grained sand, and trace small to medium gravel. *[Continued from previous page]*	516	
							22	Yellowish brown (10YR5/6) with 20% gray (10YR5/1) mottles, dry, hard, SILT with few clay, little very fine- to very coarse-grained sand, and trace small to medium gravel, horizontal and vertical fractures with dark brown (10YR3/3) oxidized faces.	514	
							24 26 28 30	Gray (10YR5/1), moist, hard, SILT with few clay, little very fine- to very coarse-grained sand, and trace small to medium gravel, horizontal and vertical fractures with dark brown (10YR3/3) oxidized faces.	512 510 508 506	
							32 34 36	Gray (10YR5/1), moist, hard, SILT with few clay, little very fine- to very coarse-grained sand, and trace small to medium gravel.	504 502 500	
							38	Gray (10YR5/1), moist, dense, very fine- to fine-grained SAND with trace silt.	498	
								Gray (10YR5/1), moist, dense, very fine- to very coarse-grained SAND with trace silt and small gravel.		
							40	Gray (10YR5/1), moist, dense, very fine- to fine-grained SAND with trace silt.		

Borehole Detail



NOTE(S): APW7 installed in borehole.

FIELD BORING LOG

HANSON

CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 11/3/2015
Finish: 11/5/2015
WEATHER: Sunny, warm, lo-70s

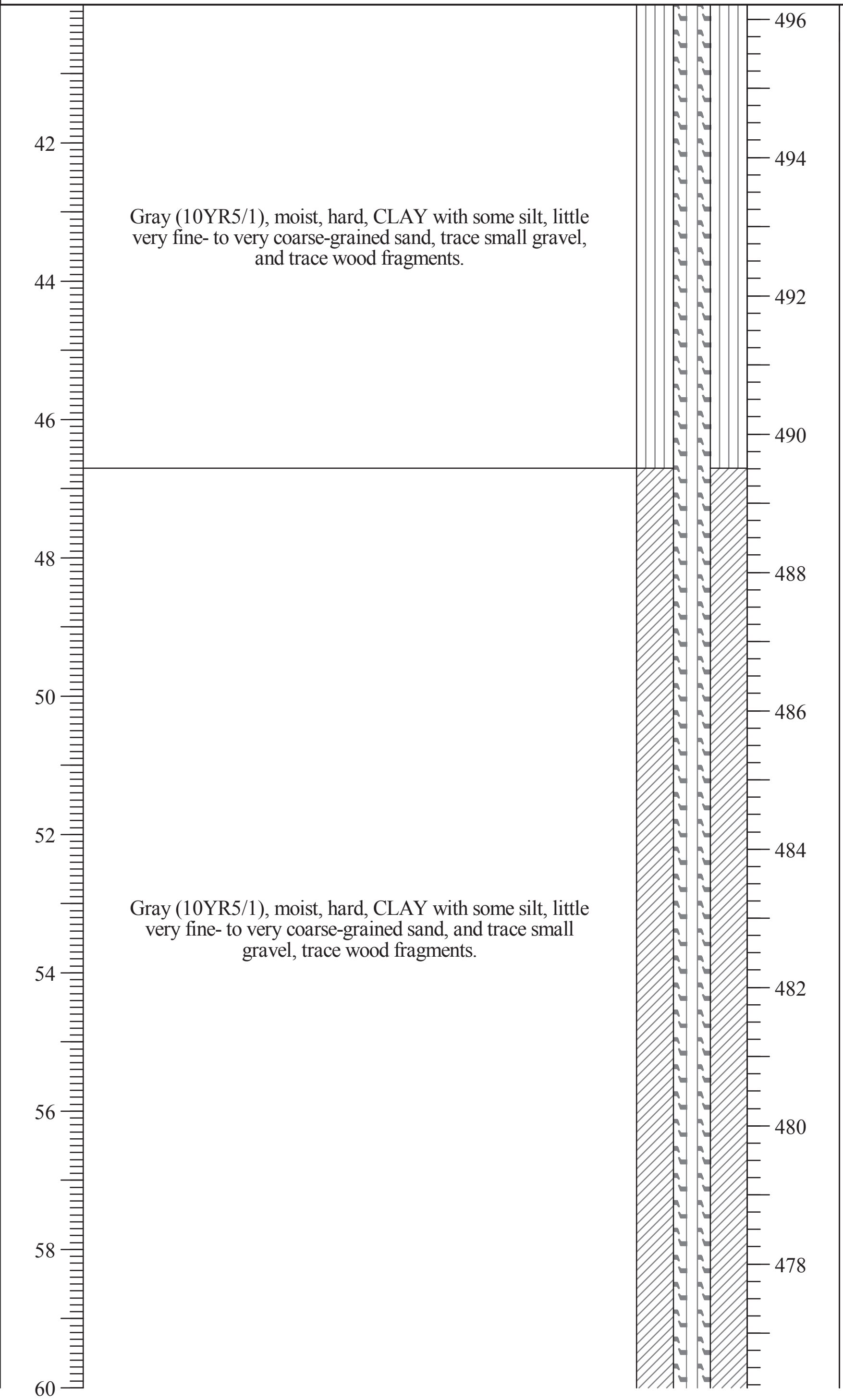
CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550X ATV Drill
Drilling Method: 4¼" HSA
FIELD STAFF: Driller: J. Gates
Helper: C. Clines
Eng/Geo: R. Hasenyager

BOREHOLE ID: APW7a
Well ID: APW7
Surface Elev: 536.21 ft. MSL
Completion: 83.10 ft. BGS
Station: 5,688.85N
6,151.60E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 26, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = Dry - During Drilling
▼ =
▽ =

SAMPLE			TESTING								
Number	Recov / Total (in) *% Recovery*	Type	*Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft^3)	Qu (tsf) *Qp* (tsf) Failure Type	Depth ft. BGS	Lithologic Description	Borehole Detail	Elevation ft. MSL	Remarks
							42–46.7	Gray (10YR5/1), moist, hard, CLAY with some silt, little very fine- to very coarse-grained sand, trace small gravel, and trace wood fragments.			
							46.7–60	Gray (10YR5/1), moist, hard, CLAY with some silt, little very fine- to very coarse-grained sand, and trace small gravel, trace wood fragments.			



NOTE(S): APW7 installed in borehole.

FIELD BORING LOG

HANSON

CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 11/3/2015
Finish: 11/5/2015
WEATHER: Sunny, warm, lo-70s

CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550X ATV Drill
Drilling Method: 4¼" HSA

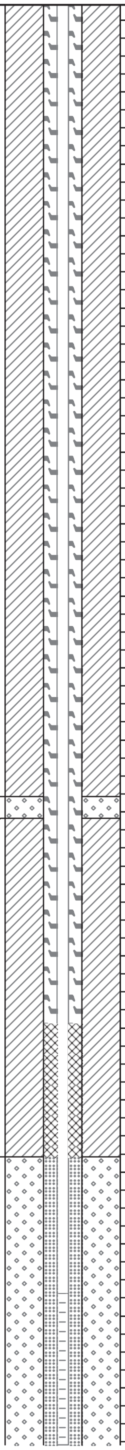
FIELD STAFF: Driller: J. Gates
Helper: C. Clines
Eng/Geo: R. Hasenyager

BOREHOLE ID: APW7a
Well ID: APW7
Surface Elev: 536.21 ft. MSL
Completion: 83.10 ft. BGS
Station: 5,688.85N
6,151.60E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 26, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = Dry - During Drilling
▼ =
▽ =

SAMPLE			TESTING								
Number	Recov / Total (in) *% Recovery*	Type	*Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft^3)	Qu (tsf) *Qp* (tsf) Failure Type	Depth ft. BGS	Lithologic Description	Borehole Detail	Elevation ft. MSL	Remarks
										476	
							62			474	
							64			472	
							66	Gray (10YR5/1), moist, hard, CLAY with some silt, little very fine- to very coarse-grained sand, and trace small gravel, trace wood fragments. *[Continued from previous page]*		470	
							68			468	
							70			466	
								Gray (10YR5/1), moist, dense, very fine- to very coarse-grained SAND with some clay and silt.			
							72			464	
							74	Gray (10YR5/1), moist, hard, CLAY with some silt, little very fine- to very coarse-grained sand, trace small gravel, and trace wood fragments.		462	
							76			460	
							78	Gray (10YR5/1), wet, loose, very fine- to very coarse-grained SAND with trace small gravel.		458	
							80				



NOTE(S): APW7 installed in borehole.

FIELD BORING LOG

HANSON

CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 11/3/2015
Finish: 11/5/2015
WEATHER: Sunny, warm, lo-70s

CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550X ATV Drill
Drilling Method: 4¼" HSA

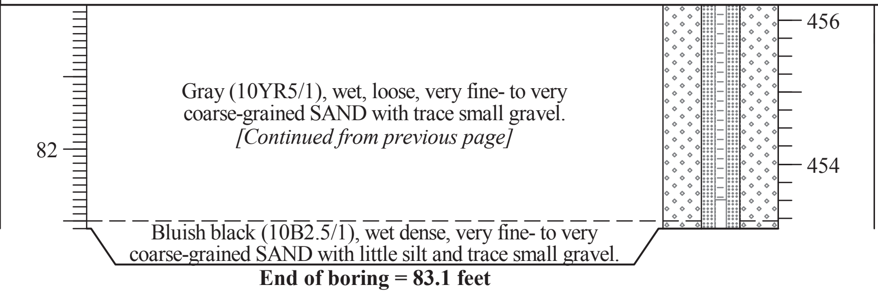
FIELD STAFF: Driller: J. Gates
Helper: C. Clines
Eng/Geo: R. Hasenyager

BOREHOLE ID: APW7a
Well ID: APW7
Surface Elev: 536.21 ft. MSL
Completion: 83.10 ft. BGS
Station: 5,688.85N
6,151.60E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 26, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = Dry - During Drilling
▼ =
▽ =

SAMPLE			TESTING								
Number	Recov / Total (in) *% Recovery*	Type	*Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft^3)	Qu (tsf) *Qp* (tsf) Failure Type	Depth ft. BGS	Lithologic Description	Borehole Detail	Elevation ft. MSL	Remarks



Gray (10YR5/1), wet, loose, very fine- to very coarse-grained SAND with trace small gravel. *[Continued from previous page]*

Bluish black (10B2.5/1), wet dense, very fine- to very coarse-grained SAND with little silt and trace small gravel.

End of boring = 83.1 feet

NOTE(S): APW7 installed in borehole.

FIELD BORING LOG

HANSON

CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 10/27/2015
Finish: 10/28/2015
WEATHER: Sunny, breezy, warm, lo-80s

CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550X ATV Drill
Drilling Method: 4¼" HSA, macro-core sampler, split spoon sampler
FIELD STAFF: Driller: C. Dutton
Helper: C. Jones
Eng/Geo: S. Keim

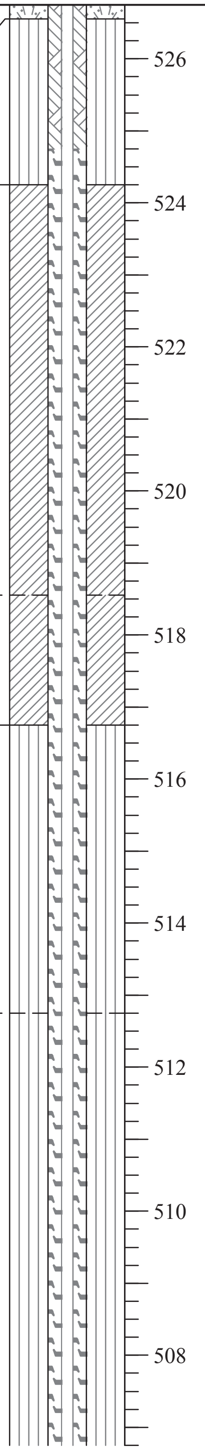
BOREHOLE ID: APW8
Well ID: APW8
Surface Elev: 526.75 ft. MSL
Completion: 82.00 ft. BGS
Station: 3,839.59N
6,082.37E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 26, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = 33.70 - During Drilling
▼ =
▽ =

SAMPLE			TESTING			
Number	Recov / Total (in) *% Recovery*	Type	*Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft^3)	Qu (tsf) *Qp (tsf)* Failure Type
1A	60/60 *100%*	DP		13		*4.50*
1B				21		*3.00*
2A	60/60 *100%*	DP		18		*2.50*
2B				28		*2.00*
3A	20/24 *83%*	DP		8		*2.00*
4A	0/17 *0%*	SS	*23-43* *50/5"*			
5A	21/24 *88%*	SS	*13-20* *24-28* N=44	10		*4.50*
6A	24/24 *100%*	SS	*7-14* *20-48* N=34	11		*4.50*
7A	24/24 *100%*	SS	*14-21* *26-32* N=47	10		

Depth ft. BGS	Lithologic Description	Remarks
	Black (10YR2/1), moist, very stiff, SILT with little clay and trace very fine- to medium-grained sand, roots.	
2	Yellowish brown (10YR5/4) with 30% light gray (10YR7/2) mottles, dry, hard, SILT with little clay and trace very fine- to medium-grained sand.	
4 6 8	Grayish brown (10YR5/2) with 15% dark yellowish brown (10YR4/6) and 10% black (10YR2/1) mottles, moist, very stiff, silty CLAY with few very fine- to coarse-grained sand and trace small gravel.	
10	Grayish brown (10YR5/2) with 15% dark yellowish brown mottles, moist, stiff, silty CLAY with few very fine- to coarse-grained sand and trace small gravel.	
12 14	Brown (10YR5/3) with 20% dark yellowish brown (10YR5/6) mottles, dry, stiff, SILT with little clay and trace very fine- to coarse-grained sand.	Rock in shoe of sampler.
16 18 20	Dark gray (10YR4/1), moist, hard, SILT with little clay, trace very fine- to coarse-grained sand and small gravel.	



NOTE(S): APW8 installed in borehole.

FIELD BORING LOG

HANSON

CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 10/27/2015
Finish: 10/28/2015
WEATHER: Sunny, breezy, warm, lo-80s

CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550X ATV Drill
Drilling Method: 4¼" HSA, macro-core sampler, split spoon sampler
FIELD STAFF: Driller: C. Dutton
Helper: C. Jones
Eng/Geo: S. Keim

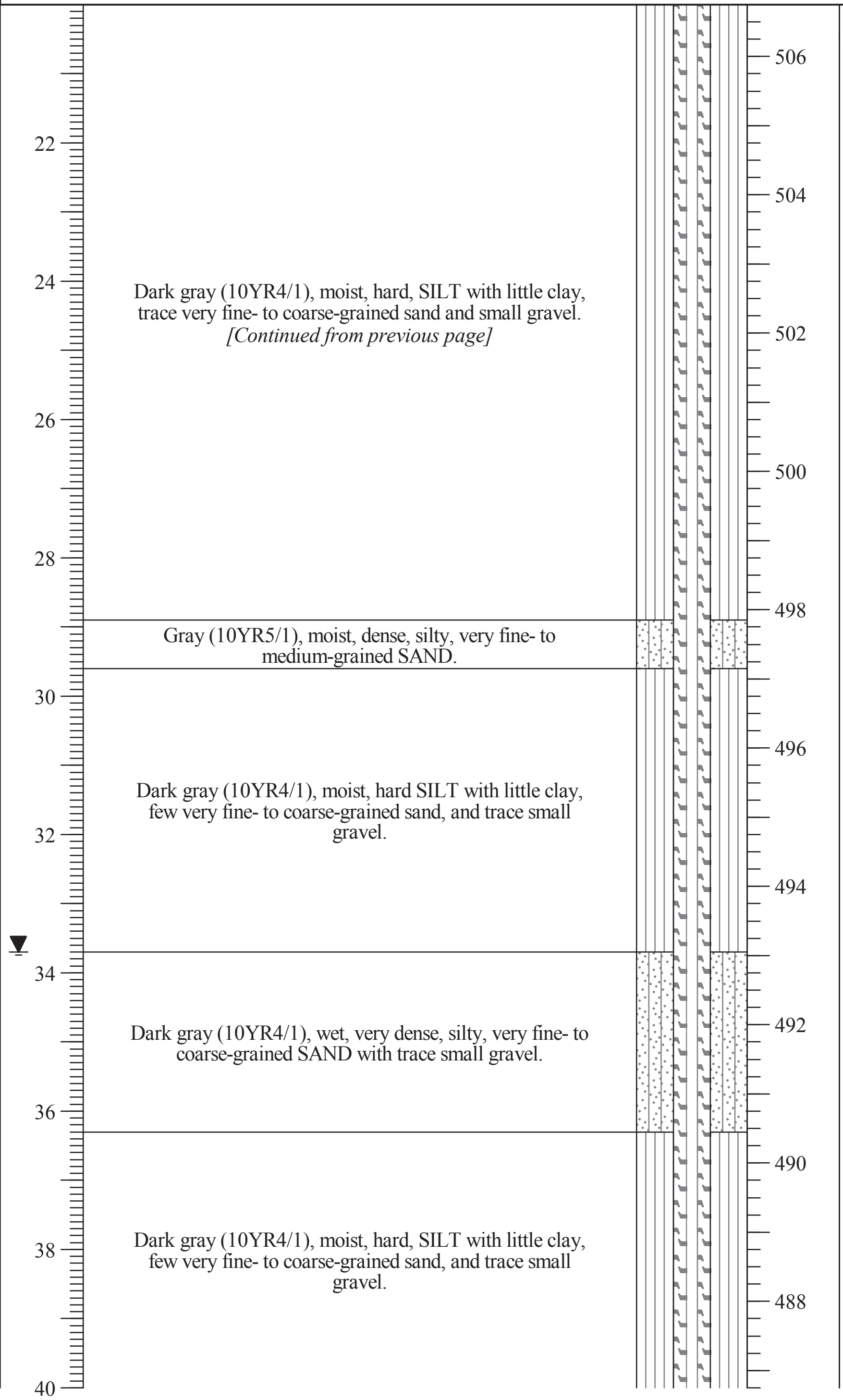
BOREHOLE ID: APW8
Well ID: APW8
Surface Elev: 526.75 ft. MSL
Completion: 82.00 ft. BGS
Station: 3,839.59N
6,082.37E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 26, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = 33.70 - During Drilling
▼ =
▽ =

SAMPLE			TESTING			
Number	Recov / Total (in) *% Recovery*	Type	*Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft³)	Qu (tsf) *Qp (tsf)* Failure Type
8A	24/24 *100%*	SS	*7-13* *19-23* N=32	11		*4.50*
9A	24/24 *100%*	SS	*7-14* *19-27* N=33	11		*4.50*
10A	24/24 *100%*	SS	*8-15* *30-37* N=45	11		*4.50*
11A	24/24 *100%*	SS	*8-16* *24-33* N=40	11		*4.50*
12A 12B	24/24 *100%*	SS	*9-31* *33-30* N=64	11 12		*4.50*
13A	24/24 *100%*	SS	*10-23* *40-35* N=63	11		*4.50*
14A	21/24 *88%*	SS	*16-16* *29-50* N=45	10		*4.50*
15A	20/24 *83%*	SS	*9-24* *34-41* N=58	13		
16A	22/24 *92%*	SS	*16-18* *29-35* N=47	11		*4.50*
17A	21/24 *88%*	SS	*10-17* *21-31* N=38	11		*4.50*

Depth ft. BGS | Lithologic Description | Borehole Detail | Elevation ft. MSL | Remarks



Dark gray (10YR4/1), moist, hard, SILT with little clay, trace very fine- to coarse-grained sand and small gravel. *[Continued from previous page]*

Gray (10YR5/1), moist, dense, silty, very fine- to medium-grained SAND.

Dark gray (10YR4/1), moist, hard SILT with little clay, few very fine- to coarse-grained sand, and trace small gravel.

Dark gray (10YR4/1), wet, very dense, silty, very fine- to coarse-grained SAND with trace small gravel.

Dark gray (10YR4/1), moist, hard, SILT with little clay, few very fine- to coarse-grained sand, and trace small gravel.

NOTE(S): APW8 installed in borehole.

FIELD BORING LOG

HANSON

CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 10/27/2015
Finish: 10/28/2015
WEATHER: Sunny, breezy, warm, lo-80s

CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550X ATV Drill
Drilling Method: 4¼" HSA, macro-core sampler, split spoon sampler
FIELD STAFF: Driller: C. Dutton
Helper: C. Jones
Eng/Geo: S. Keim

BOREHOLE ID: APW8
Well ID: APW8
Surface Elev: 526.75 ft. MSL
Completion: 82.00 ft. BGS
Station: 3,839.59N
6,082.37E

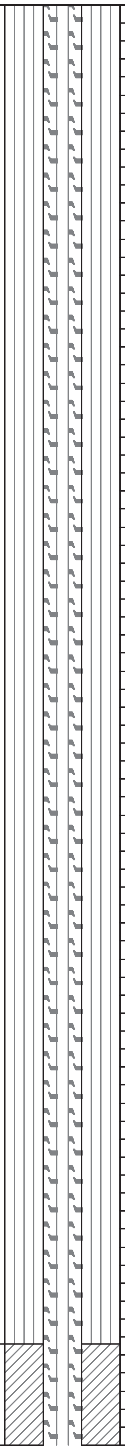
TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 26, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = 33.70 - During Drilling
▼ =
▽ =

SAMPLE Number	Recov / Total (in) *% Recovery*	Type	*Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft^3)	Qu (tsf) *Qp (tsf)* Failure Type
18A	24/24 *100%*	SS	*9-16* *26-32* N=42	11		*4.50*
19A	24/24 *100%*	SS	*10-16* *23-34* N=39	12		*4.50*
20A	24/24 *100%*	SS	*10-15* *26-44* N=41	13		*4.50*
21A	24/24 *100%*	SS	*12-21* *32-48* N=53	12		*4.50*
22A	24/24 *100%*	SS	*11-17* *22-31* N=39	13		*4.50*
23A	24/24 *100%*	SS	*10-13* *21-32* N=34	13		*4.50*
24A	24/24 *100%*	SS	*8-13* *50-26* N=63	13		*4.50*
25A	24/24 *100%*	SS	*8-11* *19-28* N=30	14		*4.25*
26A	24/24 *100%*	SS	*10-12* *18-26* N=30	13		*4.50*
27A	22/24 *92%*	SS	*7-10* *15-22* N=25	21		*4.50*

Depth ft. BGS	Lithologic Description	Elevation ft. MSL
42 44 46 48 50 52 54 56 58	Dark gray (10YR4/1), moist, hard, SILT with little clay, few very fine- to coarse-grained sand, and trace small gravel. *[Continued from previous page]*	486 484 482 480 478 476 474 472 470
60	Olive gray (5Y4/2), moist, hard, silty CLAY with few very fine- to coarse-grained sand and trace small gravel.	468

Borehole Detail



Remarks

NOTE(S): APW8 installed in borehole.

FIELD BORING LOG

HANSON

CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 10/27/2015
Finish: 10/28/2015
WEATHER: Sunny, breezy, warm, lo-80s

CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550X ATV Drill
Drilling Method: 4¼" HSA, macro-core sampler, split spoon sampler
FIELD STAFF: Driller: C. Dutton
Helper: C. Jones
Eng/Geo: S. Keim

BOREHOLE ID: APW8
Well ID: APW8
Surface Elev: 526.75 ft. MSL
Completion: 82.00 ft. BGS
Station: 3,839.59N
6,082.37E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 26, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = 33.70 - During Drilling
▼ =
▽ =

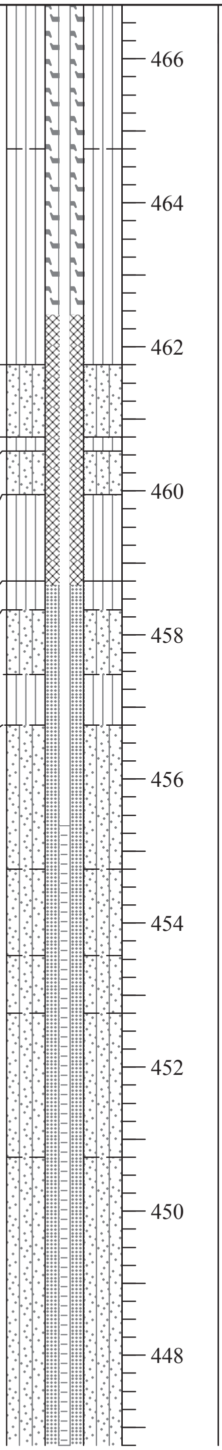
SAMPLE			TESTING			
Number	Recov / Total (in) *% Recovery*	Type	*Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft³)	Qu (tsf) *Qp (tsf)* Failure Type
28A	20/24 *83%*	ss	*7-15* *19-20* N=34	14		*4.50*
29A	21/24 *88%*	ss	*7-8* *11-16* N=19	11		*3.75*
30A	21/24 *88%*	ss	*6-13* *14-11* N=27	14		*4.00*
30B				10		
31A	18/24 *75%*	ss	*4-3* *4-3* N=7	28		
31B				15		*3.25*
32A	20/24 *83%*	ss	*1-3* *3-2* N=6	17		
32B				28		
33A	15/24 *63%*	ss	*woh-2* *6-6* N=8	17		
34A	16/24 *67%*	ss	*9-11* *15-20* N=26	9		
35A	15/24 *63%*	ss	*16-21* *23-24* N=44	9		
36A	14/24 *58%*	ss	*11-20* *25-24* N=45	11		
37A	15/24 *63%*	ss	*20-25* *24-25* N=49	10		

Depth ft. BGS	Lithologic Description
	Dark gray (10YR4/1), moist, hard, SILT with little clay, few very fine- to coarse-grained sand and trace small gravel.
62	Dark gray (10YR4/1), moist, very stiff, SILT with little clay, few very fine- to coarse-grained sand and trace small gravel.
64	Gray (10YR6/1), wet, medium dense, silty, very fine- to coarse-grained SAND with trace small to large gravel.
66	Dark gray (10YR4/1), moist, very stiff, SILT with little clay and few very fine- to coarse-grained sand.
	Dark gray (10YR4/1), wet, loose, silty, very fine- to coarse-grained SAND with trace small gravel and trace wood fragments.
	Dark gray (10YR4/1), moist, very stiff, SILT with little clay, few very fine- to coarse-grained sand, and trace small gravel, trace wood fragments.
68	Dark gray (10YR4/1), wet, loose, SILT with little very fine- to fine-grained sand.
	Dark gray (10YR4/1), wet, loose, silty, very fine- to coarse-grained SAND.
	Dark gray (10YR4/1), wet, loose, SILT with little very fine- to fine-grained sand, trace wood fragments.
70	Dark gray (10YR4/1), wet, loose, silty, very fine- to coarse-grained SAND, trace wood fragments.
72	Dark gray (10YR4/1), wet, medium dense, silty, very fine- to coarse-grained SAND with trace small gravel.
	Dark gray (10YR4/1), wet, medium dense, silty, very fine- to coarse-grained SAND with few small to large gravel.
74	Dark gray (10YR4/1), wet, dense, silty, very fine- to coarse-grained SAND with few small to large gravel.
76	Dark gray (10YR4/1), wet, dense, silty, very fine- to coarse-grained SAND with trace small gravel.
78	
80	

Borehole Detail

Elevation ft. MSL

Remarks



NOTE(S): APW8 installed in borehole.

FIELD BORING LOG

HANSON

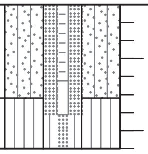
CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 10/27/2015
Finish: 10/28/2015
WEATHER: Sunny, breezy, warm, lo-80s

CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550X ATV Drill
Drilling Method: 4¼" HSA, macro-core sampler, split spoon sampler
FIELD STAFF: Driller: C. Dutton
Helper: C. Jones
Eng/Geo: S. Keim

BOREHOLE ID: APW8
Well ID: APW8
Surface Elev: 526.75 ft. MSL
Completion: 82.00 ft. BGS
Station: 3,839.59N
6,082.37E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 26, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = 33.70 - During Drilling
▼ =
▽ =

SAMPLE			TESTING								
Number	Recov / Total (in) *% Recovery*	Type	*Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft^3)	Qu (tsf) *Qp (tsf)* Failure Type	Depth ft. BGS	Lithologic Description	Borehole Detail	Elevation ft. MSL	Remarks
38A	18/24 *75%*	SS	*26-26* *26-31* N=52	8				Dark gray (10YR4/1), wet, dense, silty, very fine- to coarse-grained SAND with trace small gravel. *[Continued from previous page]*		446	
38B				11		*4.50*	82	Dark gray (10YR4/1), moist, hard, SILT with little clay and few very fine- to coarse-grained sand.			

End of boring = 82.0 feet

NOTE(S): APW8 installed in borehole.

FIELD BORING LOG

CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 11/2/2015
Finish: 11/3/2015
WEATHER: Foggy, mild, lo-50s

CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550X ATV Drill
Drilling Method: 4¼" HSA, split spoon sampler

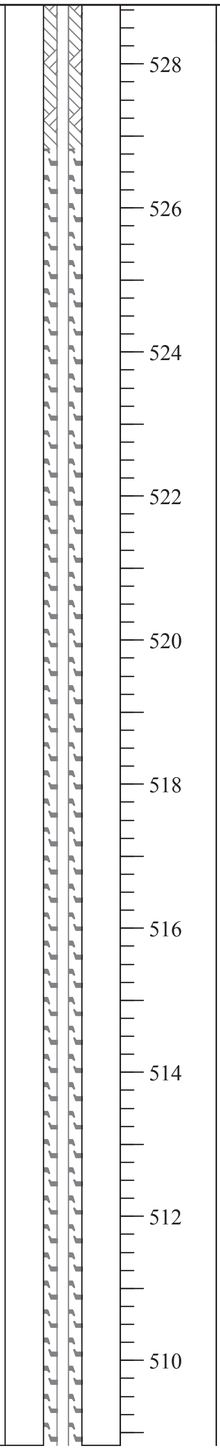
FIELD STAFF: Driller: J. Gates
Helper: C. Clines
Eng/Geo: R. Hasenyager

BOREHOLE ID: APW9
Well ID: APW9
Surface Elev: 528.82 ft. MSL
Completion: 62.00 ft. BGS
Station: 3,519.59N
9,125.33E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 26, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = 27.00 - During Drilling
▼ = 26.10 - 11/3/15
▽ =

SAMPLE			TESTING								
Number	Recov / Total (in) *% Recovery*	Type	*Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft^3)	Qu (tsf) *Qp* (tsf) Failure Type	Depth ft. BGS	Lithologic Description	Borehole Detail	Elevation ft. MSL	Remarks
1	0/60 *0%*	BD					0–5	Blind drill - see APW3 boring log for lithology, sample, and testing data			
2	0/60 *0%*	BD					5–10				
3	0/60 *0%*	BD					10–15				
4	0/60 *0%*	BD					15–20				



NOTE(S): APW9 installed in borehole.
Lithology, sample, and testing data can be found on APW-3 Field Boring Log.

FIELD BORING LOG

CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 11/2/2015
Finish: 11/3/2015
WEATHER: Foggy, mild, lo-50s

CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550X ATV Drill
Drilling Method: 4¼" HSA, split spoon sampler
FIELD STAFF: Driller: J. Gates
Helper: C. Clines
Eng/Geo: R. Hasenyager

HANSON
BOREHOLE ID: APW9
Well ID: APW9
Surface Elev: 528.82 ft. MSL
Completion: 62.00 ft. BGS
Station: 3,519.59N
9,125.33E

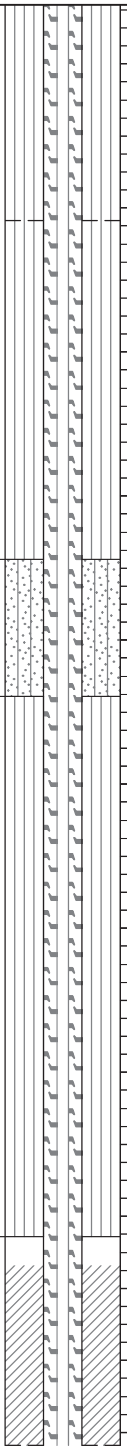
TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 26, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = 27.00 - During Drilling
▼ = 26.10 - 11/3/15
▽ =

SAMPLE			TESTING				
Number	Recov / Total (in) *% Recovery*	Type	*Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft³)	Qu (tsf) *Qp (tsf)* Failure Type	Remarks
5A	24/24 *100%*	SS	*10-13 21-28* N=34	10		*4.25*	
6A	24/24 *100%*	SS	*13-15 21-29* N=36	10		*4.50*	
7A	2/24 *8%*	SS	*15-28 33-39* N=61	11		*4.50*	Rock in shoe of sampler.
8A	23/23 *100%*	SS	*9-15 39-50/5"* N=54	11			
8B				11			
9A	24/24 *100%*	SS	*12-22 28-27* N=50	11			
9B				12		*4.50*	
10A	24/24 *100%*	SS	*14-22 32-44* N=54	11		*4.50*	
11A	23/24 *96%*	SS	*8-16 24-35* N=40	11		*4.50*	
12A	16/24 *67%*	SS	*12-25 35-32* N=60	12		*4.50*	
13A	24/24 *100%*	SS	*6-12 24-25* N=36	11		*4.50*	
14A	24/24 *100%*	SS	*4-7 16-32* N=23	14		*4.50*	

Depth ft. BGS	Lithologic Description
20–23	Gray (10YR5/1), moist, hard, SILT with some very fine-grained sand, little clay, and trace small to medium gravel. Vertical and horizontal fractures with yellowish brown (10YR5/8) faces.
23–27.7	Gray (10YR5/1), moist, hard, SILT with some very fine-grained sand, little clay, and trace small to medium gravel.
27.7–29.6	Gray (10YR5/1), wet, dense, very fine- to very coarse-grained SAND with some silt, few clay and trace small to medium gravel.
29.6–37.1	Gray (10YR5/1), moist, hard, SILT with little clay and very fine-grained sand and trace small gravel.
37.1–40	Gray (10YR5/1) moist, stiff, CLAY with some silt, little very fine-grained sand and trace small gravel.

Depth ft. BGS: 22, 24, ▼ 26, ▼, 28, 30, 32, 34, 36, 38, 40



Elevation ft. MSL: 508, 506, 504, 502, 500, 498, 496, 494, 492, 490

NOTE(S): APW9 installed in borehole.
Lithology, sample, and testing data can be found on APW-3 Field Boring Log.

FIELD BORING LOG

HANSON

CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 11/2/2015
Finish: 11/3/2015
WEATHER: Foggy, mild, lo-50s

CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550X ATV Drill
Drilling Method: 4¼" HSA, split spoon sampler
FIELD STAFF: Driller: J. Gates
Helper: C. Clines
Eng/Geo: R. Hasenyager

BOREHOLE ID: APW9
Well ID: APW9
Surface Elev: 528.82 ft. MSL
Completion: 62.00 ft. BGS
Station: 3,519.59N
9,125.33E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 26, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = 27.00 - During Drilling
▼ = 26.10 - 11/3/15
▽ =

SAMPLE			TESTING			
Number	Recov / Total (in) *% Recovery*	Type	*Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft^3)	Qu (tsf) *Qp (tsf)* Failure Type
15A	24/24 *100%*	SS	*5-11* *19-23* N=30	14		*4.50*
16A	24/24 *100%*	SS	*4-8* *14-29* N=22	15		*4.50*
16B				12		
17A	24/24 *100%*	SS	*8-17* *24-34* N=41	11		*4.50*
18A	24/24 *100%*	SS	*7-13* *20-29* N=33	12		*4.50*
19A	24/24 *100%*	SS	*6-12* *18-24* N=30	12		*4.50*
20A	24/24 *100%*	SS	*7-12* *17-22* N=29	15		*4.50*
21A	24/24 *100%*	SS	*5-11* *12-18* N=23	14		*4.25*
22A	23/23 *100%*	SS	*6-14* *24-50/5"* N=38	13		*4.50*
22B				13		
23A	24/24 *100%*	SS	*7-15* *21-30* N=36	13		
24A	18/24 *75%*	SS	*13-38* *43-40* N=81	15		

Depth ft. BGS — Lithologic Description — Borehole Detail — Elevation ft. MSL — Remarks

42 44 46 48 50 52 54 56 58 60

Gray (10YR5/1) moist, stiff, CLAY with some silt, little very fine-grained sand and trace small gravel, trace wood fragments.

Light olive brown (2.5Y5/3), moist, stiff, CLAY with some silt, few very fine- to very coarse-grained sand, and trace small gravel.

Light olive brown (2.5Y5/3) with 30% yellowish brown (10YR5/8) mottles, moist, stiff, CLAY with some silt, few very fine- to very coarse-grained sand, and trace small gravel.

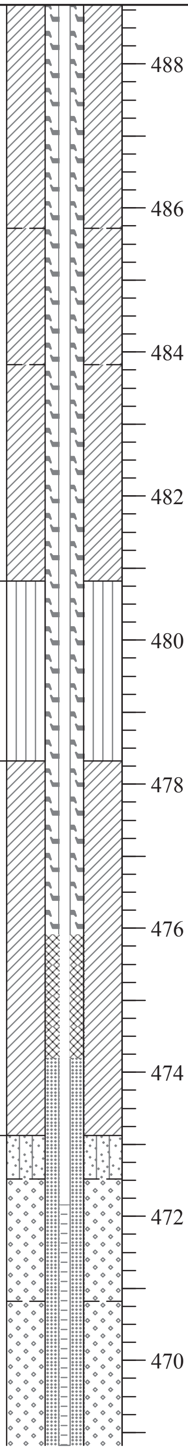
Grayish brown (2.5Y5/2) with 10% gray (2.5Y5/3) mottles, moist, hard, SILT with little very fine- to very coarse-grained sand, few clay and trace small to large gravel.

Yellowish brown (10YR5/6) with 25% gray (10YR6/1) mottles, moist, stiff, CLAY with some silt, little very fine-medium-grained sand, and trace small gravel.

Dark gray (10YR4/1), moist, dense, very fine- to fine-grained SAND with few silt.

Gray (10YR5/1), wet, loose, very fine- to very coarse-grained SAND with trace small gravel.

Gray (10YR5/1), wet, loose, very fine- to coarse-grained SAND.



NOTE(S): APW9 installed in borehole.
Lithology, sample, and testing data can be found on APW-3 Field Boring Log.

FIELD BORING LOG

HANSON

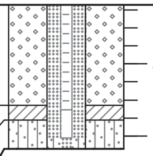
CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 11/2/2015
Finish: 11/3/2015
WEATHER: Foggy, mild, lo-50s

CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550X ATV Drill
Drilling Method: 4¼" HSA, split spoon sampler
FIELD STAFF: Driller: J. Gates
Helper: C. Clines
Eng/Geo: R. Hasenyager

BOREHOLE ID: APW9
Well ID: APW9
Surface Elev: 528.82 ft. MSL
Completion: 62.00 ft. BGS
Station: 3,519.59N
9,125.33E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 26, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = 27.00 - During Drilling
▼ = 26.10 - 11/3/15
▽ =

SAMPLE			TESTING									
Number	Recov / Total (in) *% Recovery*	Type	*Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft^3)	Qu (tsf) *Qp (tsf)* Failure Type	Depth ft. BGS	Lithologic Description	Borehole Detail	Elevation ft. MSL	Remarks
25A	24/24 *100%*	SS	*4-18* *25-30* N=43	21				Gray (10YR5/1), wet, loose, very fine- to coarse-grained SAND. *[Continued from previous page]*		468	
								Gray (10YR5/1), moist, stiff, CLAY with some silt and trace very fine-grained sand.			
25B				16			62	Gray (10YR5/1), wet, dense, SILT and very fine-grained SAND.			

End of boring = 62.0 feet

NOTE(S): APW9 installed in borehole.
Lithology, sample, and testing data can be found on APW-3 Field Boring Log.

Surface Elevation: 528.47

Datum msl

Completion Date: 6/18/10

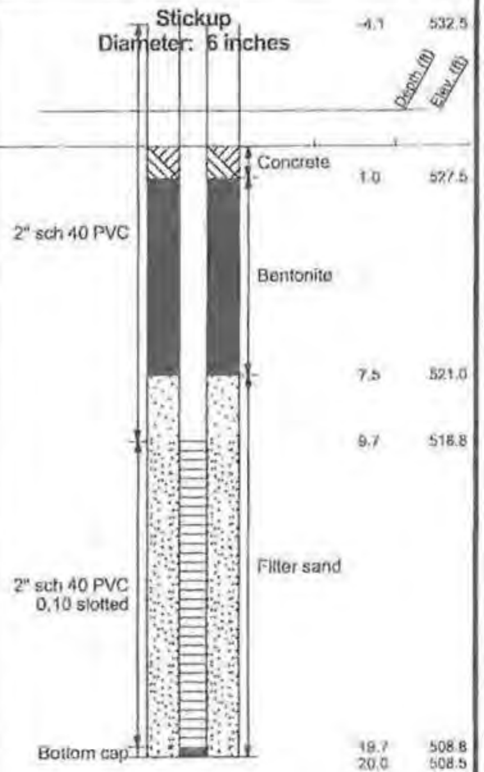
Northing: 821379.76

Easting: 998975.74

DEPTH IN FEET	DESCRIPTION OF MATERIAL	GRAPHIC LOG	DRY UNIT WEIGHT (pcf) SPT BLOW COUNTS CORE RECOVERY/RQD	SAMPLES
	Soft, brown, silty CLAY - CL	▨		
5		▨		
	Soft, brown, sandy CLAY with gravel - CL	▨		
	Hard, brown, sandy CLAY with gravel - CL	▨		
10		▨		
	Hard, brownish-gray, sandy CLAY with gravel - CL	▨		
15		▨		
20	Boring terminated at 20 feet.			
25				
30				
35				

NOTE: STRATIFICATION LINES REPRESENT THE APPROXIMATE BOUNDARIES BETWEEN SOIL TYPES AND THE TRANSITION MAY BE GRADUAL. GRAPHIC LOG FOR ILLUSTRATION PURPOSES ONLY.

WELL DIAGRAM



GROUNDWATER DATA

X FREE WATER NOT ENCOUNTERED DURING DRILLING

DRILLING DATA

4 1/4" AUGER __ HOLLOW STEM

WASHBORING FROM __ FEET

MVU DRILLER KCR LOGGER

CME 750X DRILL RIG

HAMMER TYPE Auto

REMARKS:

Drawn by: KA	Checked by: RSF	App'vd. by: DTK
Date: 6/29/10	Date: 2/7/11	Date: 2-7-11

GEOTECHNOLOGY INC
FROM THE GROUND UP

Ameren Power Plant
Newton, Illinois

LOG OF BORING: APW-3

Project No. J017150.01

FIELD BORING LOG

HANSON

CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 10/27/2015
Finish: 10/27/2015
WEATHER: Cool, rainy, lo-50s

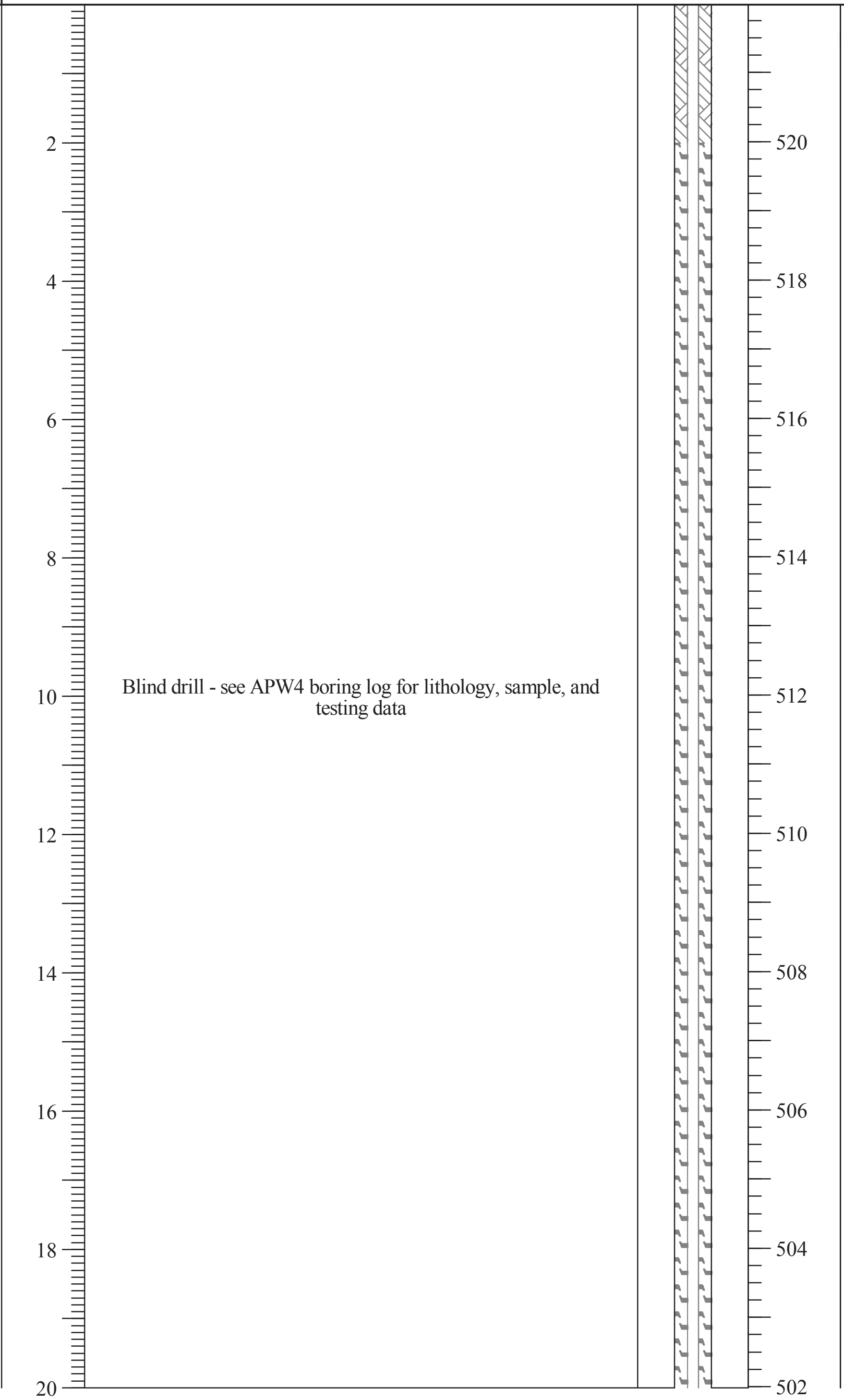
CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550X ATV Drill
Drilling Method: 4¼" HSA
FIELD STAFF: Driller: C. Dutton
Helper: C. Jones
Eng/Geo: S. Keim

BOREHOLE ID: APW10a
Well ID: APW10
Surface Elev: 521.98 ft. MSL
Completion: 45.94 ft. BGS
Station: 5,371.32N
11,541.23E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 25, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = 36.00 - During Drilling
▼ =
▽ =

SAMPLE			TESTING								
Number	Recov / Total (in) *% Recovery*	Type	*Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft^3)	Qu (tsf) *Qp* (tsf) Failure Type	Depth ft. BGS	Lithologic Description	Borehole Detail	Elevation ft. MSL	Remarks



Blind drill - see APW4 boring log for lithology, sample, and testing data

NOTE(S): APW10 installed in borehole.
Lithology, sample, and testing data can be found on APW-4 Field Boring Log.

FIELD BORING LOG

HANSON

CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 10/27/2015
Finish: 10/27/2015
WEATHER: Cool, rainy, lo-50s

CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550X ATV Drill
Drilling Method: 4¼" HSA

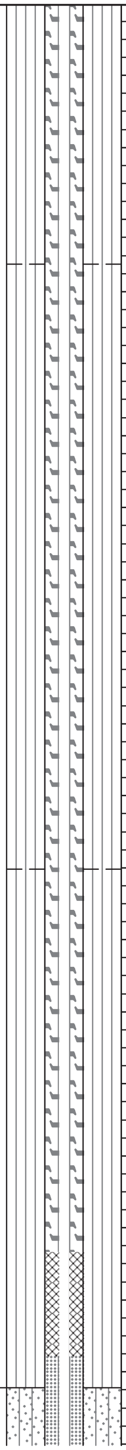
FIELD STAFF: Driller: C. Dutton
Helper: C. Jones
Eng/Geo: S. Keim

BOREHOLE ID: APW10a
Well ID: APW10
Surface Elev: 521.98 ft. MSL
Completion: 45.94 ft. BGS
Station: 5,371.32N
11,541.23E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 25, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = 36.00 - During Drilling
▼ =
▽ =

SAMPLE			TESTING								
Number	Recov / Total (in) *% Recovery*	Type	*Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft³)	Qu (tsf) *Qp (tsf)* Failure Type	Depth ft. BGS	Lithologic Description	Borehole Detail	Elevation ft. MSL	Remarks
							22	Yellowish brown (10YR5/6) with 5% gray (N6/1) mottles, moist, hard, SILT with little clay, few very fine-grained sand, and trace small gravel.		500	
							24	Yellowish brown (10YR5/4) with 5% dark yellowish brown (10YR4/6) and 5% gray (N6/1) mottles, moist, hard, SILT with little clay, few very fine-grained sand, and trace small gravel.		498	
							26			496	
							28			494	
							30			492	
							32	Brown (10YR5/3) with 5% gray (N6/1) mottles, moist, hard, SILT with little clay, few very fine-grained sand, and trace small gravel.		490	
							34			488	
							▼ 36			486	
							38			484	
							40	Brown (10YR5/3), wet, very dense, silty, very fine- to medium-grained SAND with trace small gravel.		482	



NOTE(S): APW10 installed in borehole.
Lithology, sample, and testing data can be found on APW-4 Field Boring Log.

FIELD BORING LOG

HANSON

CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 10/27/2015
Finish: 10/27/2015
WEATHER: Cool, rainy, lo-50s

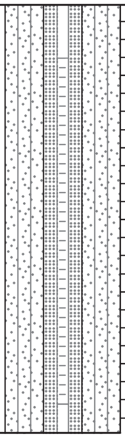
CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550X ATV Drill
Drilling Method: 4¼" HSA
FIELD STAFF: Driller: C. Dutton
Helper: C. Jones
Eng/Geo: S. Keim

BOREHOLE ID: APW10a
Well ID: APW10
Surface Elev: 521.98 ft. MSL
Completion: 45.94 ft. BGS
Station: 5,371.32N
11,541.23E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 25, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = 36.00 - During Drilling
▼ =
▽ =

SAMPLE			TESTING								
Number	Recov / Total (in) *% Recovery*	Type	*Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft³)	Qu (tsf) *Qp* (tsf) Failure Type	Depth ft. BGS	Lithologic Description	Borehole Detail	Elevation ft. MSL	Remarks
							42 44	Brown (10YR5/3), wet, very dense, silty, very fine- to medium-grained SAND with trace small gravel. *[Continued from previous page]*		480 478	



End of boring = 45.94 feet

NOTE(S): APW10 installed in borehole.
Lithology, sample, and testing data can be found on APW-4 Field Boring Log.

FIELD BORING LOG

HANSON

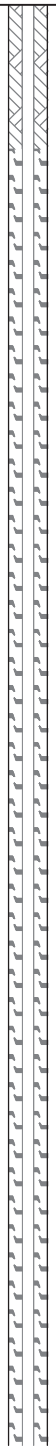
CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 11/9/2015
Finish: 11/10/2015
WEATHER: Sunny, mild, lo-60s

CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550 ATV Drill
Drilling Method: 4¼" HSA, split spoon sampler
FIELD STAFF: Driller: J. Gates
Helper: C. Clines
Eng/Geo: R. Hasenyager

BOREHOLE ID: G06D
Well ID: G06D
Surface Elev: 529.69 ft. MSL
Completion: 96.00 ft. BGS
Station: 5,328.80N
4,925.99E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 26, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = Dry - During Drilling
▼ =
▽ =

SAMPLE			TESTING								
Number	Recov / Total (in) *% Recovery*	Type	*Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft³)	Qu (tsf) *Qp* (tsf) Failure Type	Depth ft. BGS	Lithologic Description	Borehole Detail	Elevation ft. MSL	Remarks
1	0/60 *0%*	BD					2 4			528 526	
2	0/60 *0%*	BD					6 8 10	Blind drill - see G106 boring log for lithology, sample, and testing data		524 522 520	
3	0/60 *0%*	BD					12 14			518 516	
4	0/60 *0%*	BD					16 18 20			514 512 510	

NOTE(S): G06D installed in borehole.
Lithology, sample, and testing data can be found on G106 Field Boring Log.

FIELD BORING LOG

HANSON

CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 11/9/2015
Finish: 11/10/2015
WEATHER: Sunny, mild, lo-60s

CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550 ATV Drill
Drilling Method: 4¼" HSA, split spoon sampler
FIELD STAFF: Driller: J. Gates
Helper: C. Clines
Eng/Geo: R. Hasenyager

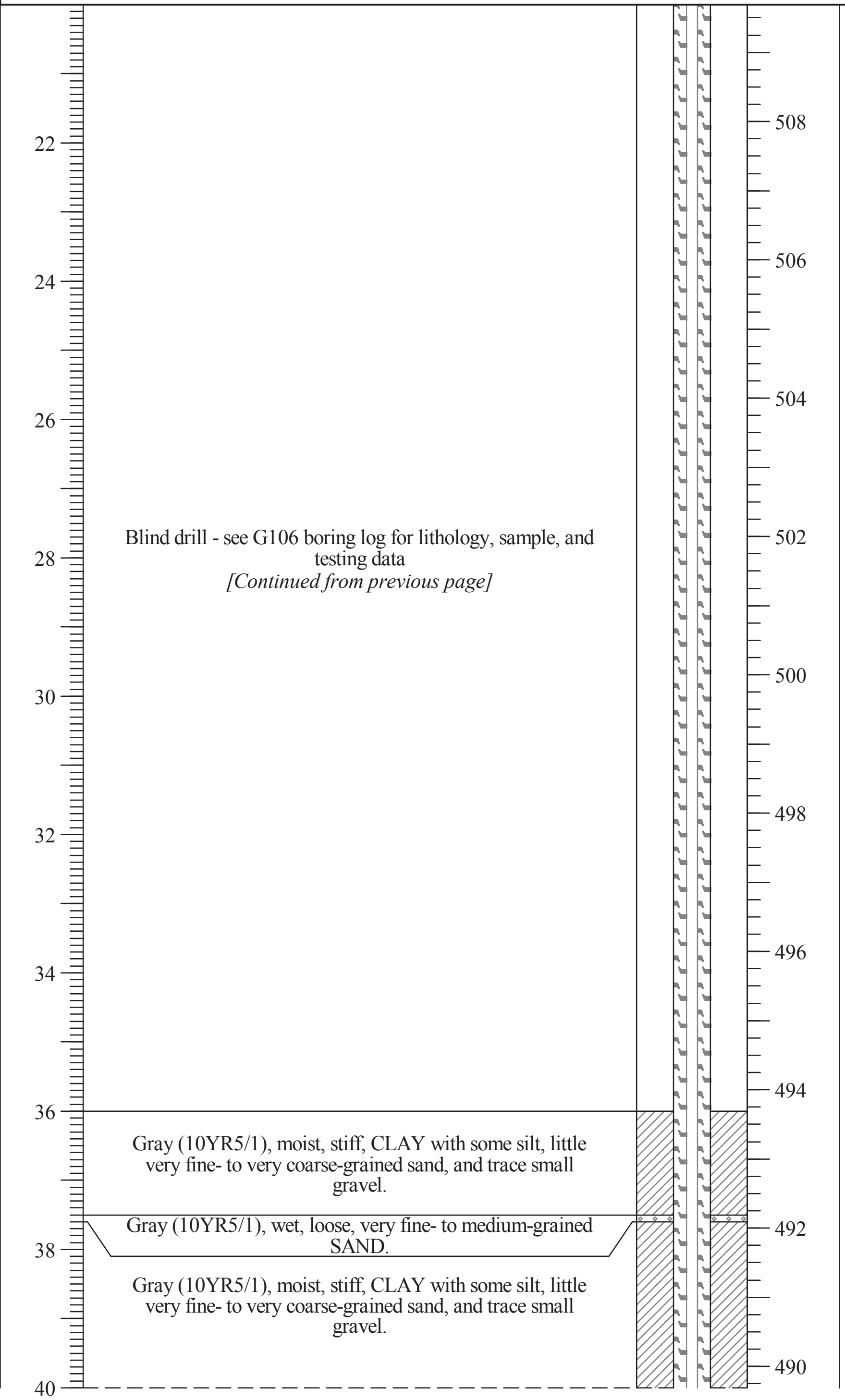
BOREHOLE ID: G06D
Well ID: G06D
Surface Elev: 529.69 ft. MSL
Completion: 96.00 ft. BGS
Station: 5,328.80N
4,925.99E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 26, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = Dry - During Drilling
▼ =
▽ =

SAMPLE			TESTING			
Number	Recov / Total (in) *% Recovery*	Type	*Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft^3)	Qu (tsf) *Qp (tsf)* Failure Type
	0/60 *0%*	BD				
5						
	0/60 *0%*	BD				
6						
	0/60 *0%*	BD				
7						
	0/12 *0%*	BD				
8						
9A	24/24 *100%*	SS	*3-8* *12-15* N=20	13		*3.75*
10A	14/24 *58%*	SS	*6-11* *19-22* N=30	14		*4.00*

Depth ft. BGS | Lithologic Description | Borehole Detail | Elevation ft. MSL | Remarks



Blind drill - see G106 boring log for lithology, sample, and testing data
[Continued from previous page]

Gray (10YR5/1), moist, stiff, CLAY with some silt, little very fine- to very coarse-grained sand, and trace small gravel.

Gray (10YR5/1), wet, loose, very fine- to medium-grained SAND.

Gray (10YR5/1), moist, stiff, CLAY with some silt, little very fine- to very coarse-grained sand, and trace small gravel.

NOTE(S): G06D installed in borehole.
Lithology, sample, and testing data can be found on G106 Field Boring Log.

FIELD BORING LOG

HANSON

CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 11/9/2015
Finish: 11/10/2015
WEATHER: Sunny, mild, lo-60s

CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550 ATV Drill
Drilling Method: 4¼" HSA, split spoon sampler
FIELD STAFF: Driller: J. Gates
Helper: C. Clines
Eng/Geo: R. Hasenyager

BOREHOLE ID: G06D
Well ID: G06D
Surface Elev: 529.69 ft. MSL
Completion: 96.00 ft. BGS
Station: 5,328.80N
4,925.99E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 26, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = Dry - During Drilling
▼ =
▽ =

SAMPLE			TESTING			
Number	Recov / Total (in) *% Recovery*	Type	*Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft^3)	Qu (tsf) *Qp (tsf)* Failure Type
11A	24/24 *100%*	SS	*3-7* *13-16* N=20	12		*4.50*
12A	24/24 *100%*	SS	*3-7* *11-12* N=18	13		*4.50*
13A	24/24 *100%*	SS	*6-8* *12-14* N=20	14		*4.50*
14A	3/24 *13%*	SS	*13-14* *16-20* N=30	13		
15A	23/24 *96%*	SS	*3-7* *11-14* N=18	13		*4.50*
16A	24/24 *100%*	SS	*5-9* *11-15* N=20	15		*4.00*
17A	21/24 *88%*	SS	*10-14* *12-15* N=26	13		*3.75*
18A	23/24 *96%*	SS	*4-7* *10-14* N=17	14		*3.25*
19A	24/24 *100%*	SS	*2-4* *9-12* N=13	15		*3.25*
20A	24/24 *100%*	SS	*3-7* *10-14* N=17	13		*3.50*

Depth ft. BGS: 42, 44, 46, 48, 50, 52, 54, 56, 58, 60

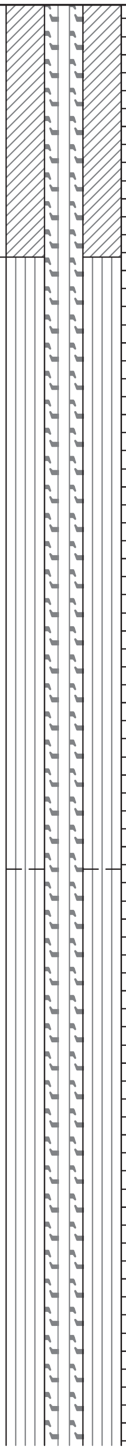
Lithologic Description

Gray (10YR5/1), moist, hard, CLAY with some silt, few very fine- to medium-grained sand, and trace small gravel.

Gray (10YR5/1), moist, hard, SILT with some clay, little very fine- to very coarse-grained sand, and trace small gravel, trace wood fragments.

Gray (10YR5/1), moist, hard, SILT with some clay, little very fine- to very coarse-grained sand, and trace small to medium gravel, trace wood fragments.

Borehole Detail



Elevation ft. MSL: 488, 486, 484, 482, 480, 478, 476, 474, 472, 470

Remarks

NOTE(S): G06D installed in borehole.
Lithology, sample, and testing data can be found on G106 Field Boring Log.

FIELD BORING LOG

HANSON

CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 11/9/2015
Finish: 11/10/2015
WEATHER: Sunny, mild, lo-60s

CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550 ATV Drill
Drilling Method: 4¼" HSA, split spoon sampler
FIELD STAFF: Driller: J. Gates
Helper: C. Clines
Eng/Geo: R. Hasenyager

BOREHOLE ID: G06D
Well ID: G06D
Surface Elev: 529.69 ft. MSL
Completion: 96.00 ft. BGS
Station: 5,328.80N
4,925.99E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 26, **Tier** 6N; **Range** 8E

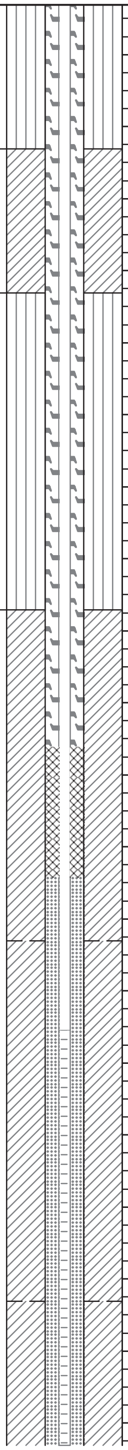
WATER LEVEL INFORMATION:
▼ = Dry - During Drilling
▼ =
▽ =

SAMPLE Number	Recov / Total (in) *% Recovery*	Type	TESTING *Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft³)	Qu (tsf) *Qp (tsf)* Failure Type
21A	24/24 *100%*	SS	*4-8 11-16* N=19	13		*4.25*
22A	24/24 *100%*	SS	*2-6 10-14* N=16	14		*3.75*
23A	24/24 *100%*	SS	*6-10 16-21* N=26	13		*4.50*
24A	24/24 *100%*	SS	*4-8 11-14* N=19	13		*4.50*
25A	24/24 *100%*	SS	*2-6 8-9* N=14	15		*3.60*
26A	24/24 *100%*	SS	*1-4 8-9* N=12	17		*2.75*
27A	24/24 *100%*	SS	*woh-4 5-8* N=9	18		*2.25*
28A	24/24 *100%*	SS	*woh-3 5-8* N=8	17		*1.50*
29A	24/24 *100%*	SS	*wor-1 5-7* N=6	18		*1.50*
30A	24/24 *100%*	SS	*1-4 5-8* N=9	19		*1.00*

Depth ft. BGS	Lithologic Description
to 62	Gray (10YR5/1), moist, hard, SILT with some clay, little very fine- to very coarse-grained sand, and trace small to medium gravel, trace wood fragments. *[Continued from previous page]*
62–64	Gray (10YR5/1), moist, hard, CLAY with some silt, little very fine- to very coarse-grained sand, and trace small to medium gravel, trace wood fragments.
64–68.4	Gray (10YR5/1), moist, hard, SILT with some clay, little very fine- to very coarse-grained sand, and trace small to medium gravel, trace wood fragments.
68.4–73	Gray (10YR5/1), moist, stiff, CLAY with some silt, little very fine- to very coarse-grained sand, and trace small gravel, trace wood fragments.
73–78	Gray (10YR5/1), moist, medium, CLAY with some silt, little very fine- to very coarse-grained sand, and trace small gravel, trace wood fragments.
78–80	Gray (10YR5/1), moist, soft, CLAY with some silt, little very fine- to very coarse-grained sand, and trace small gravel, trace wood fragments.

Depth ft. BGS: 62, 64, 66, 68, 70, 72, 74, 76, 78, 80

Borehole Detail



Elevation ft. MSL: 468, 466, 464, 462, 460, 458, 456, 454, 452, 450

Remarks

NOTE(S): G06D installed in borehole.
Lithology, sample, and testing data can be found on G106 Field Boring Log.

FIELD BORING LOG

HANSON

CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 11/9/2015
Finish: 11/10/2015
WEATHER: Sunny, mild, lo-60s

CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550 ATV Drill
Drilling Method: 4¼" HSA, split spoon sampler
FIELD STAFF: Driller: J. Gates
Helper: C. Clines
Eng/Geo: R. Hasenyager

BOREHOLE ID: G06D
Well ID: G06D
Surface Elev: 529.69 ft. MSL
Completion: 96.00 ft. BGS
Station: 5,328.80N
4,925.99E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 26, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = Dry - During Drilling
▼ =
▽ =

SAMPLE			TESTING			
Number	Recov / Total (in) *% Recovery*	Type	*Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft^3)	Qu (tsf) *Qp (tsf)* Failure Type
31A	24/24 *100%*	SS	*woh-3* *5-8* N=8	19		*0.75*
32A	24/24 *100%*	SS	*1-4* *6-8* N=10	18		*1.25*
33A	24/24 *100%*	SS	*woh-4* *6-8* N=10	19		*1.00*
34A	24/24 *100%*	SS	*woh-4* *9-10* N=13	16		*1.00*
34B				18		
35A	24/24 *100%*	SS	*4-9* *7-8* N=16	19		*1.25*
36A	24/24 *100%*	SS	*woh-2* *5-6* N=7	20		*0.75*
37A	24/24 *100%*	SS	*woh-2* *5-7* N=7	19		*0.75*
38A	24/24 *100%*	SS	*woh-3* *5-8* N=8	19		*0.75*

Depth ft. BGS | Lithologic Description | Borehole Detail | Elevation ft. MSL | Remarks

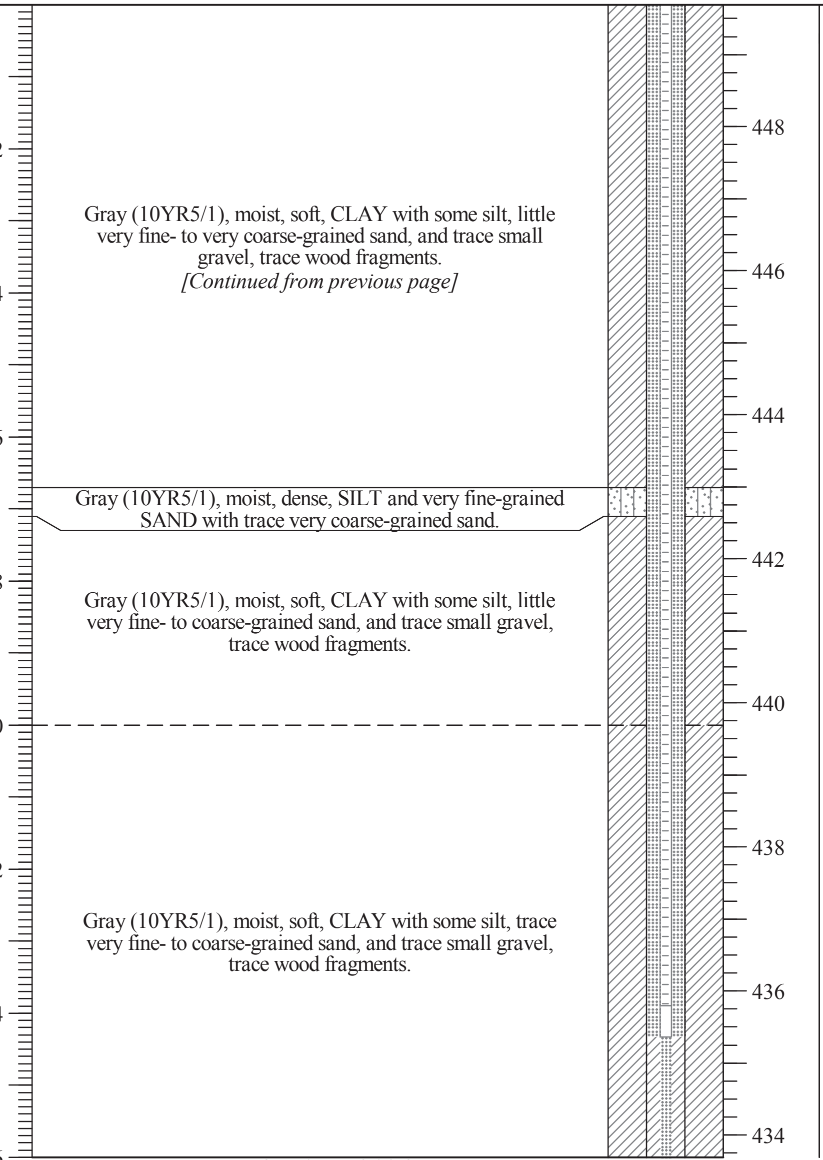
Gray (10YR5/1), moist, soft, CLAY with some silt, little very fine- to very coarse-grained sand, and trace small gravel, trace wood fragments.
[Continued from previous page]

Gray (10YR5/1), moist, dense, SILT and very fine-grained SAND with trace very coarse-grained sand.

Gray (10YR5/1), moist, soft, CLAY with some silt, little very fine- to coarse-grained sand, and trace small gravel, trace wood fragments.

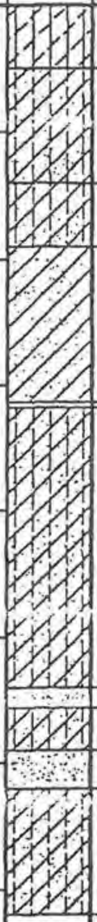
Gray (10YR5/1), moist, soft, CLAY with some silt, trace very fine- to coarse-grained sand, and trace small gravel, trace wood fragments.

End of boring = 96.0 feet



NOTE(S): G06D installed in borehole.
Lithology, sample, and testing data can be found on G106 Field Boring Log.

CIPS NEWTON POWER STATION	BORING G-106	SHEET 1 of 1
DATE STARTED 8/1/90	DATE COMPLETED 8/1/90	LOGGED BY RAB
SURFACE EL. 529.0		
DRILLING CONTRACTOR: BROTCKE ENG.		DRILL METHOD: H.S. AUGER



Depth (ft)	N-Value	SOIL/ROCK DESCRIPTION	VAPOR CONCENTRATION (ppm) 10^0 10^1 10^2 10^3	COMMENTS
0	22	Brn. clayey SILT, tr. roots, blocky, dry.		
	20 18	Brn. sandy silty CLAY, tr. pebbles, sl. moist, blocky.		
	33	Mottled gray & brn. silty sandy CLAY, tr. pebbles, moist.		
10	50 72 50	Brn. sandy CLAY, tr. pebbles, vert. med. sand filled fract., so. mn & iron oxid., moist.		
		Brn. coarse SAND.		
20	80 43 59 45	Gray brn. sandy silty CLAY, tr. pebbles, coal frag., oxid. vert. fract., hard.		
	9	Gray coarse – v. coarse SAND.		▽
	63	Gray sandy silty CLAY, tr. pebbles, moist.		
30		Coarse – v. coarse SAND grading downward to gravel.		
	39 33	Gray sandy silty CLAY, tr. pebbles, unweathered.		
		End of Boring = 36.0'		
40				

SOIL/ROCK BORING DATA

HANSON ENGINEERS INCORPORATED

PAC	11-19-90
REVIEWED	DATE
RKC	11-19-90
APPROVED	DATE

CIPS
NEWTON POWER STATION
NEWTON, ILLINOIS

JOB NO. 89S5008A

FIELD BORING LOG

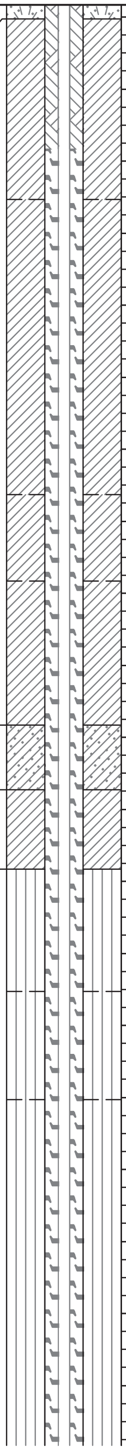
CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 10/19/2015
Finish: 10/20/2015
WEATHER: Sunny, breezy, warm, lo-80s

CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550X ATV Drill
Drilling Method: 4¼" HSA
FIELD STAFF: Driller: C. Dutton
Helper: C. Jones
Eng/Geo: S. Keim

BOREHOLE ID: G48MG
Well ID: G48MG
Surface Elev: 543.17 ft. MSL
Completion: 77.06 ft. BGS
Station: 9,706.71N
5,052.58E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 23, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = Dry - During Drilling
▼ =
▽ =



SAMPLE Number	Recov / Total (in) *% Recovery*	Type	TESTING *Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft^3)	Qu (tsf) *Qp* (tsf) Failure Type	Depth ft. BGS	Lithologic Description	Elevation ft. MSL	Remarks
								Grayish brown (10YR5/2), moist, very soft, silty CLAY, trace roots.		
								Grayish brown (10YR5/2) with 30% dark yellowish brown (10YR4/6) mottles, moist, soft, silty CLAY, slight trace roots.	542	
							2			
									540	
							4			
								Brown (10YR5/3) with 30% dark yellowish brown (10YR4/6) mottles, moist, soft, silty CLAY with trace sand and slight trace gravel.	538	
							6			
								Gray (10YR5/1) with 20% dark yellowish brown (10YR4/6) mottles, moist, soft, silty CLAY with trace sand and slight trace gravel.	536	
							8			
								Gray (10YR5/1) with 40% dark yellowish brown (10YR4/6) mottles, very moist, soft, silty CLAY with trace sand and slight trace gravel.	534	
							10			
								Yellowish brown (10YR5/4) with 10% gray (10YR6/1) mottles, soft, wet, sandy CLAY with slight trace gravel.		
								Yellowish brown (10YR5/4) with 10% gray (10YR5/1) mottles, moist, firm, silty CLAY with trace sand and slight trace gravel.	532	
							12			
								Dark gray (10YR4/1) with 30% brown (10YR4/3) mottles, slightly moist, hard, clayey SILT with trace sand and slight trace gravel.	530	
							14			
								Dark gray (10YR4/1) with 20% dark grayish brown (10YR4/2) mottles, slightly moist, hard, clayey SILT with trace sand and slight trace gravel.	528	
							16			
								Dark gray (10YR4/1), slightly moist, hard, clayey SILT with trace sand and slight trace gravel.	526	
							18			
									524	
							20			

NOTE(S): G48MG installed in borehole.
Sample and testing data can be found on B-48 Field Boring Log.

FIELD BORING LOG

HANSON

CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 10/19/2015
Finish: 10/20/2015
WEATHER: Sunny, breezy, warm, lo-80s

CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550X ATV Drill
Drilling Method: 4¼" HSA
FIELD STAFF: Driller: C. Dutton
Helper: C. Jones
Eng/Geo: S. Keim

BOREHOLE ID: G48MG
Well ID: G48MG
Surface Elev: 543.17 ft. MSL
Completion: 77.06 ft. BGS
Station: 9,706.71N
5,052.58E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 23, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = Dry - During Drilling
▼ =
▽ =

SAMPLE			TESTING			
Number	Recov / Total (in) *% Recovery*	Type	*Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft^3)	Qu (tsf) *Qp* (tsf) Failure Type

Depth ft. BGS: 22, 24, 26, 28, 30, 32, 34, 36, 38, 40

Lithologic Description:

Dark gray (10YR4/1), slightly moist, hard, clayey SILT with trace sand and slight trace gravel. *[Continued from previous page]*

Dark gray (10YR4/1), moist, firm, silty CLAY with slight trace sand and gravel.

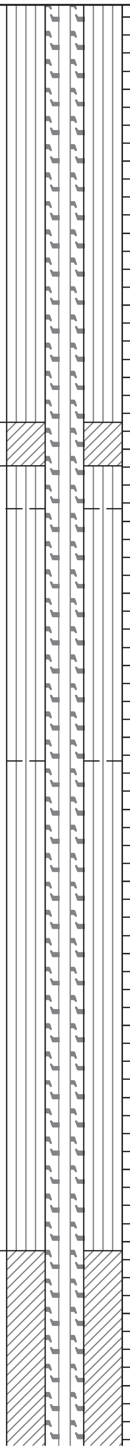
Dark gray (10YR4/1), slightly moist, hard, clayey SILT with trace sand and slight trace gravel.

Dark gray (10YR4/1), slightly moist, firm, clayey SILT with trace sand and slight trace gravel.

Dark gray (10YR4/1), slightly moist, hard, clayey SILT with trace sand and slight trace gravel.

Dark gray (10YR4/1), slightly moist, hard, silty CLAY with slight trace sand and gravel.

Borehole Detail



Elevation ft. MSL: 522, 520, 518, 516, 514, 512, 510, 508, 506, 504

Remarks

NOTE(S): G48MG installed in borehole.
Sample and testing data can be found on B-48 Field Boring Log.

FIELD BORING LOG

HANSON

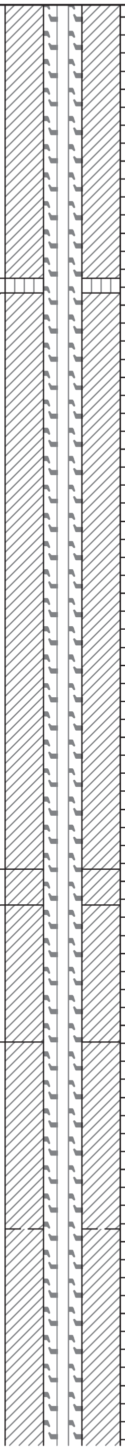
CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 10/19/2015
Finish: 10/20/2015
WEATHER: Sunny, breezy, warm, lo-80s

CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550X ATV Drill
Drilling Method: 4¼" HSA
FIELD STAFF: Driller: C. Dutton
Helper: C. Jones
Eng/Geo: S. Keim

BOREHOLE ID: G48MG
Well ID: G48MG
Surface Elev: 543.17 ft. MSL
Completion: 77.06 ft. BGS
Station: 9,706.71N
5,052.58E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 23, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = Dry - During Drilling
▼ =
▽ =



SAMPLE: Number	SAMPLE: Recov / Total (in) *% Recovery*	SAMPLE: Type	TESTING: *Blows / 6 in* N - Value **RQD**	TESTING: Moisture (%)	TESTING: Dry Den. (lb/ft³)	TESTING: Qu (tsf) *Qp* (tsf) Failure Type	Depth ft. BGS	Lithologic Description	Borehole Detail	Elevation ft. MSL	Remarks
										502	
							42	Dark gray (10YR4/1), slightly moist, hard, silty CLAY with slight trace sand and gravel. *[Continued from previous page]*			
										500	
							44	Dark gray (10YR4/1), slightly moist, firm, SILT with slight trace sand.			
										498	
							46				
										496	
							48	Dark gray (10YR4/1), slightly moist, hard, silty CLAY with slight trace sand and gravel.			
										494	
							50				
										492	
							52	Olive gray (5Y4/2), slightly moist, firm, silty CLAY with slight trace sand and gravel.			
								Dark greenish gray (10Y4/1) with 20% greenish gray (10Y6/1) mottles, slightly moist, hard, silty CLAY with trace sand and slight trace gravel.		490	
							54				
										488	
							56	Olive gray (5Y4/2) with 15% dark gray (N4/1) mottles, slightly moist, hard, silty CLAY with slight trace sand and gravel.			
										486	
							58	Olive gray (5Y4/2) with 15% dark gray (N4/1) mottles, slightly moist, firm, silty CLAY with slight trace sand and gravel.			
										484	
							60				

NOTE(S): G48MG installed in borehole.
Sample and testing data can be found on B-48 Field Boring Log.

FIELD BORING LOG

HANSON

CLIENT: AEG Newton Power Station
Site: Gypsum Management Facility
Location: Newton, Jasper Co., IL
Project: 07E0150A 3000
DATES: Start: 5/12/2009
Finish: 5/14/2009
WEATHER: Sunny, warm, windy, (mid-60's)

CONTRACTOR: Skinner Limited
Rig mfg/model: CME-550 ATV Drill
Drilling Method: 4¼" hollow stem auger w/split spoon sampler
FIELD STAFF: Driller: T. Skinner
Helper: T. Skinner/J. Austin
Eng/Geo: S. Suzanna Simpson

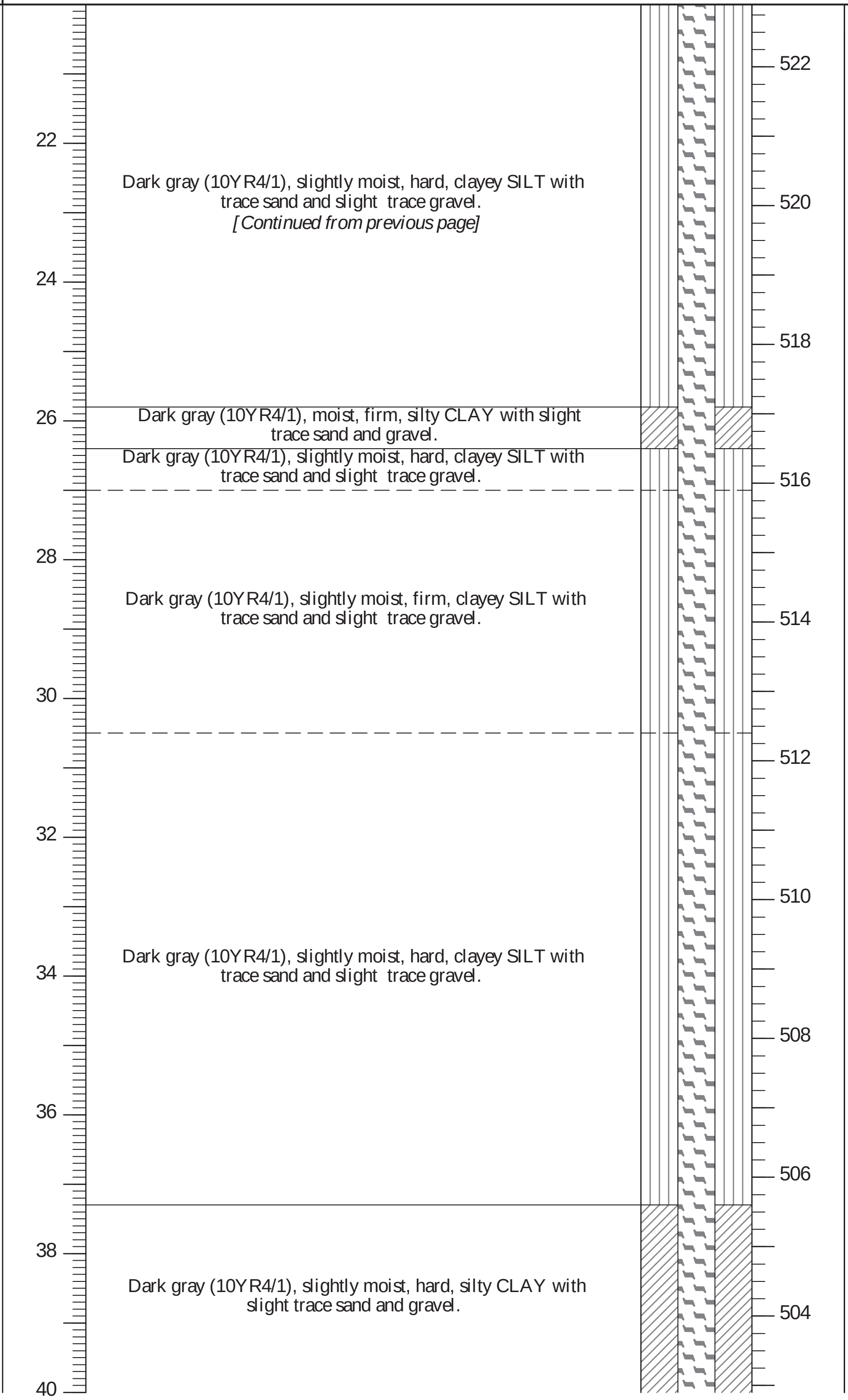
BOREHOLE ID: B48
Well ID: n/a
Surface Elev: 542.9 ft. MSL
Completion: 103.5 ft. BGS
Station: 9,703.88N
5,042.40E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 23, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = 10.00 - during drilling
▼ =
▽ =

SAMPLE			TESTING			
Number	Recov / Total (in) % Recovery	Type	Blows / 6 in N - Value RQD	Moisture (%)	Dry Den. (lb/ft³)	Qu (tsf) Qp (tsf) Failure Type
13A	24/24 100%	SS	8-13 17-17 N=30	10.1		12.36 Sh
14A	18/18 100%	SS	7-11 14 N=25	10.1		10.47 Sh
15A	18/18 100%	SS	7-11 13 N=24	9.9		9.31 Sh
16A	24/24 100%	SS	5-7 12-14 N=19	11.4		11.06 Sh
16B				16.3		2.13 BSh
17A	18/18 100%	SS	4-6 11 N=17	11.2		6.79 Sh
18A	18/18 100%	SS	5-9 16 N=25	11.4		9.70 Sh
19A	24/24 100%	SS	4-8 14-19 N=22	10.4		10.47 Sh
20A	18/18 100%	SS	6-13 17 N=30	11.4		
21A	18/18 100%	SS	7-13 19 N=32	11.3		10.28 Sh
22A	24/24 100%	SS	7-12 19-22 N=31	10.3		11.44 Sh
23A	18/18 100%	SS	6-12 19 N=31	11.5		10.86 Sh
24A	18/18 100%	SS	7-11 19 N=30	12.7		5.24 Sh

Depth ft. BGS | Lithologic Description | Borehole Detail | Elevation ft. MSL | Remarks



Dark gray (10YR4/1), slightly moist, hard, clayey SILT with trace sand and slight trace gravel.
[Continued from previous page]

Dark gray (10YR4/1), moist, firm, silty CLAY with slight trace sand and gravel.

Dark gray (10YR4/1), slightly moist, hard, clayey SILT with trace sand and slight trace gravel.

Dark gray (10YR4/1), slightly moist, firm, clayey SILT with trace sand and slight trace gravel.

Dark gray (10YR4/1), slightly moist, hard, clayey SILT with trace sand and slight trace gravel.

Dark gray (10YR4/1), slightly moist, hard, silty CLAY with slight trace sand and gravel.

NOTE(S): Borehole abandoned using bentonite grout.

FIELD BORING LOG

HANSON

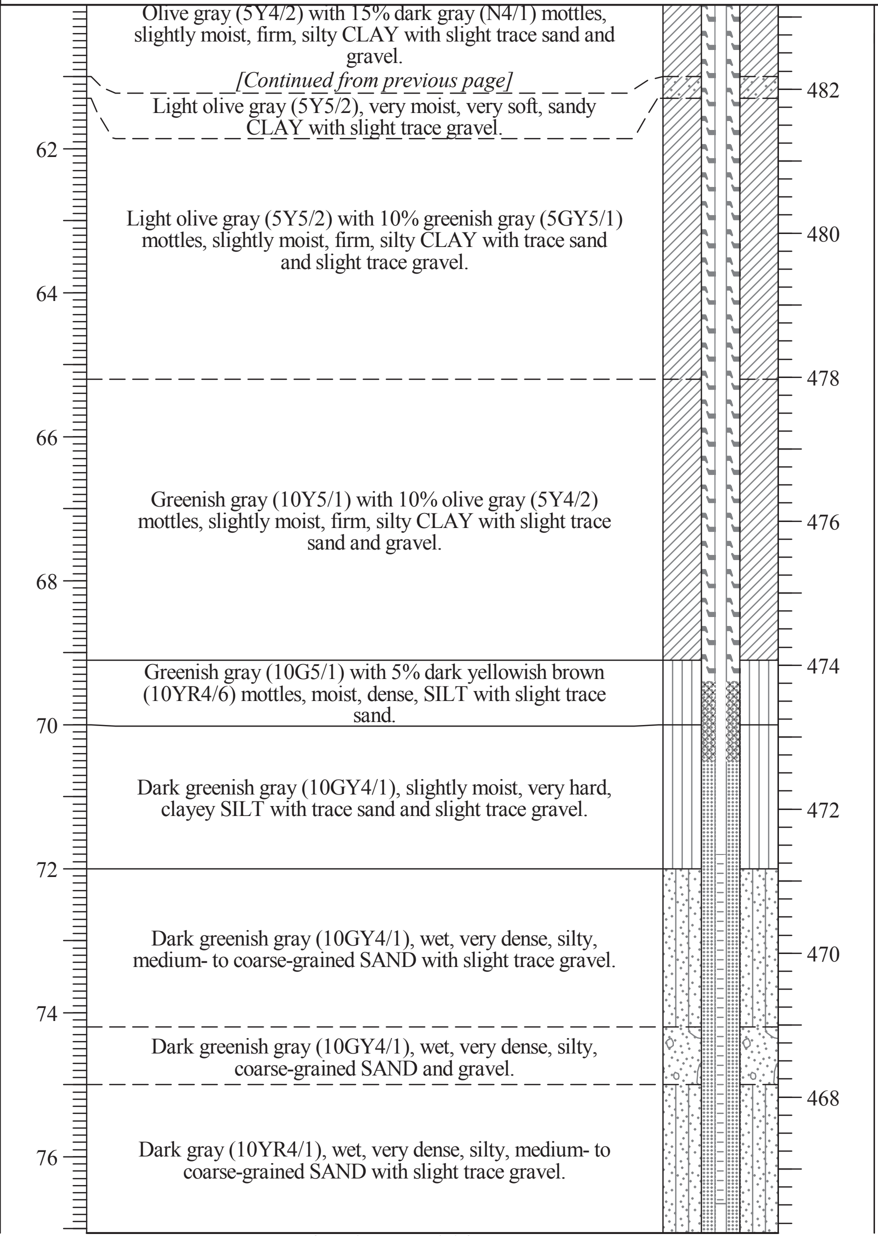
CLIENT: Natural Resource Technology, Inc.
Site: Newton Energy Center
Location: Newton, Illinois
Project: 15E0030
DATES: Start: 10/19/2015
Finish: 10/20/2015
WEATHER: Sunny, breezy, warm, lo-80s

CONTRACTOR: Bulldog Drilling, Inc.
Rig mfg/model: CME-550X ATV Drill
Drilling Method: 4¼" HSA
FIELD STAFF: Driller: C. Dutton
Helper: C. Jones
Eng/Geo: S. Keim

BOREHOLE ID: G48MG
Well ID: G48MG
Surface Elev: 543.17 ft. MSL
Completion: 77.06 ft. BGS
Station: 9,706.71N
5,052.58E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 23, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = Dry - During Drilling
▼ =
▽ =



SAMPLE			TESTING								
Number	Recov / Total (in) *% Recovery*	Type	*Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft^3)	Qu (tsf) *Qp* (tsf) Failure Type	Depth ft. BGS	Lithologic Description	Borehole Detail	Elevation ft. MSL	Remarks
								Olive gray (5Y4/2) with 15% dark gray (N4/1) mottles, slightly moist, firm, silty CLAY with slight trace sand and gravel. *[Continued from previous page]*			
								Light olive gray (5Y5/2), very moist, very soft, sandy CLAY with slight trace gravel.			
								Light olive gray (5Y5/2) with 10% greenish gray (5GY5/1) mottles, slightly moist, firm, silty CLAY with trace sand and slight trace gravel.			
								Greenish gray (10Y5/1) with 10% olive gray (5Y4/2) mottles, slightly moist, firm, silty CLAY with slight trace sand and gravel.			
								Greenish gray (10G5/1) with 5% dark yellowish brown (10YR4/6) mottles, moist, dense, SILT with slight trace sand.			
								Dark greenish gray (10GY4/1), slightly moist, very hard, clayey SILT with trace sand and slight trace gravel.			
								Dark greenish gray (10GY4/1), wet, very dense, silty, medium- to coarse-grained SAND with slight trace gravel.			
								Dark greenish gray (10GY4/1), wet, very dense, silty, coarse-grained SAND and gravel.			
								Dark gray (10YR4/1), wet, very dense, silty, medium- to coarse-grained SAND with slight trace gravel.			

End of boring = 77.06 feet

NOTE(S): G48MG installed in borehole.
Sample and testing data can be found on B-48 Field Boring Log.

FIELD BORING LOG

HANSON

CLIENT: AEG Newton Power Station
Site: Gypsum Management Facility
Location: Newton, Jasper Co., IL
Project: 07E0150A 3000
DATES: Start: 5/12/2009
Finish: 5/14/2009
WEATHER: Sunny, warm, windy, (mid-60's)

CONTRACTOR: Skinner Limited
Rig mfg/model: CME-550 ATV Drill
Drilling Method: 4¼" hollow stem auger w/split spoon sampler
FIELD STAFF: Driller: T. Skinner
Helper: T. Skinner/J. Austin
Eng/Geo: S. Suzanna Simpson

BOREHOLE ID: B48
Well ID: n/a
Surface Elev: 542.9 ft. MSL
Completion: 103.5 ft. BGS
Station: 9,703.88N
5,042.40E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 23, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = 10.00 - during drilling
▼ =
▽ =

SAMPLE			TESTING			
Number	Recov / Total (in) *% Recovery*	Type	*Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft³)	Qu (tsf) *Qp (tsf)* Failure Type
1A	13/18 *72%*	SS	*woh-2* *3* N=5	25.8		
2A	17/18 *94%*	SS	*2-3* *4* N=7	22.0		3.88 Sh
3A	17/18 *94%*	SS	*2-4* *4* N=8	15.7		1.90 Sh
4A	24/24 *100%*	SS	*woh-1* *2-3* N=3	20.5		1.78 BSh
5A	18/18 *100%*	SS	*1-1* *2* N=3	22.7		1.40 Sh
6A	24/24 *100%*	SS	*1-2* *3-3* N=5	18.3		1.27 Sh
7-1	23/24 *96%*	SH				
7-2				19.9		
7-3				15.0		
7-4				19.5		
8A	18/18 *100%*	SS	*8-13* *17* N=30	10.2		8.92 Sh
9A	18/18 *100%*	SS	*6-12* *17* N=29	9.7		5.62 Sh
10A	24/24 *100%*	SS	*7-14* *20-20* N=34	9.0		7.18 Sh
11A	18/18 *100%*	SS	*6-14* *15* N=29	8.5		9.89 Sh
12A	18/18 *100%*	SS	*5-12* *14* N=26	10.2		11.25 Sh

Depth ft. BGS | Lithologic Description | Borehole Detail | Elevation ft. MSL | Remarks

Depth: 2, 4, 6, 8, ▼ 10, 12, 14, 16, 18, 20

Grayish brown (10YR5/2), moist, very soft, silty CLAY, trace roots.

Grayish brown (10YR5/2) with 30% dark yellowish brown (10YR4/6) mottles, moist, soft, silty CLAY, slight trace roots.

Brown (10YR5/3) with 30% dark yellowish brown (10YR4/6) mottles, moist, soft, silty CLAY with trace sand and slight trace gravel.

Gray (10YR5/1) with 20% dark yellowish brown (10YR4/6) mottles, moist, soft, silty CLAY with trace sand and slight trace gravel.

Gray (10YR5/1) with 40% dark yellowish brown (10YR4/6) mottles, very moist, soft, silty CLAY with trace sand and slight trace gravel.

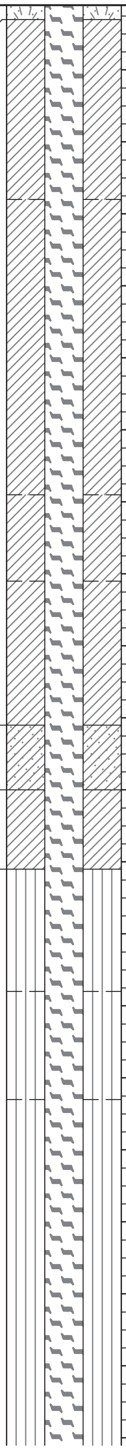
Yellowish brown (10YR5/4) with 10% gray (10YR6/1) mottles, soft, wet, sandy CLAY with slight trace gravel.

Yellowish brown (10YR5/4) with 10% gray (10YR5/1) mottles, moist, firm, silty CLAY with trace sand and slight trace gravel.

Dark gray (10YR4/1) with 30% brown (10YR4/3) mottles, slightly moist, hard, clayey SILT with trace sand and slight trace gravel.

Dark gray (10YR4/1) with 20% dark grayish brown (10YR4/2) mottles, slightly moist, hard, clayey SILT with trace sand and slight trace gravel.

Dark gray (10YR4/1), slightly moist, hard, clayey SILT with trace sand and slight trace gravel.



Elevation: 542, 540, 538, 536, 534, 532, 530, 528, 526, 524

NOTE(S): Borehole abandoned using bentonite grout.

FIELD BORING LOG

HANSON

CLIENT: AEG Newton Power Station
Site: Gypsum Management Facility
Location: Newton, Jasper Co., IL
Project: 07E0150A 3000
DATES: Start: 5/12/2009
Finish: 5/14/2009
WEATHER: Sunny, warm, windy, (mid-60's)

CONTRACTOR: Skinner Limited
Rig mfg/model: CME-550 ATV Drill
Drilling Method: 4¼" hollow stem auger w/split spoon sampler
FIELD STAFF: Driller: T. Skinner
Helper: T. Skinner/J. Austin
Eng/Geo: S. Suzanna Simpson

BOREHOLE ID: B48
Well ID: n/a
Surface Elev: 542.9 ft. MSL
Completion: 103.5 ft. BGS
Station: 9,703.88N
5,042.40E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 23, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = 10.00 - during drilling
▼ =
▽ =

SAMPLE			TESTING			
Number	Recov / Total (in) *% Recovery*	Type	*Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft³)	Qu (tsf) *Qp (tsf)* Failure Type
25A	24/24 *100%*	SS	*8-12* *22-26* N=34	11.5		10.47 Sh
26A	18/18 *100%*	SS	*7-12* *18* N=30	11.7		7.76 Sh
27A 27B	18/18 *100%*	SS	*7-15* *18* N=33	13.1 10.9		11.64 Sh
28A	24/24 *100%*	SS	*8-10* *16-21* N=26	13.7		
29A	18/18 *100%*	SS	*7-10* *16* N=26	14.5		5.82 Sh
30A	18/18 *100%*	SS	*4-9* *13* N=22	14.1		2.52 B
31-1 31-2 31-3 31-4	19/24 *79%*	SH		14.0		
32A 32B	18/18 *100%*	SS	*7-13* *19* N=32	12.9 12.5		10.28 Sh 8.92 Sh
33A 33B	18/18 *100%*	SS	*5-10* *16* N=26	14.9 14.6		2.13 BSh 6.59 Sh
34A	24/24 *100%*	SS	*6-10* *16-19* N=26	15.5		3.88 Sh
35A	18/18 *100%*	SS	*2-7* *14* N=21	18.2		1.94 BSh
36A	18/18 *100%*	SS	*3-7* *14* N=21	13.8		5.04 BSh

Depth ft. BGS | Lithologic Description | Borehole Detail | Elevation ft. MSL | Remarks

Dark gray (10YR4/1), slightly moist, hard, silty CLAY with slight trace sand and gravel.
[Continued from previous page]

Dark gray (10YR4/1), slightly moist, firm, SILT with slight trace sand.

Dark gray (10YR4/1), slightly moist, hard, silty CLAY with slight trace sand and gravel.

Olive gray (5Y4/2), slightly moist, firm, silty CLAY with slight trace sand and gravel.

Dark greenish gray (10Y4/1) with 20% greenish gray (10Y6/1) mottles, slightly moist, hard, silty CLAY with trace sand and slight trace gravel.

Olive gray (5Y4/2) with 15% dark gray (N4/1) mottles, slightly moist, hard, silty CLAY with slight trace sand and gravel.

Olive gray (5Y4/2) with 15% dark gray (N4/1) mottles, slightly moist, firm, silty CLAY with slight trace sand and gravel.

NOTE(S): Borehole abandoned using bentonite grout.

FIELD BORING LOG

HANSON

CLIENT: AEG Newton Power Station
Site: Gypsum Management Facility
Location: Newton, Jasper Co., IL
Project: 07E0150A 3000
DATES: Start: 5/12/2009
Finish: 5/14/2009
WEATHER: Sunny, warm, windy, (mid-60's)

CONTRACTOR: Skinner Limited
Rig mfg/model: CME-550 ATV Drill
Drilling Method: 4¼" hollow stem auger w/split spoon sampler
FIELD STAFF: Driller: T. Skinner
Helper: T. Skinner/J. Austin
Eng/Geo: S. Suzanna Simpson

BOREHOLE ID: B48
Well ID: n/a
Surface Elev: 542.9 ft. MSL
Completion: 103.5 ft. BGS
Station: 9,703.88N
5,042.40E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 23, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = 10.00 - during drilling
▼ =
▽ =

SAMPLE Number	Recov / Total (in) *% Recovery*	Type	TESTING *Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft³)	Qu (tsf) *Qp (tsf)* Failure Type
37-1				16.5		1.75 BSh
37-2	19/24 *79%*	SH		12.7		3.50 None
37-3				15.0		
37-4						
38A	18/18 *100%*	SS	*8-13* *15* N=28	14.5		3.10 B
39A	18/18 *100%*	SS	*6-9* *15* N=24	12.8		5.04 BSh
40A	24/24 *100%*	SS	*4-9* *13-15* N=22	13.6		5.43 Sh
41A	18/18 *100%*	SS	*12-13* *14* N=27	13.2		4.07 BSh
42A	16/17 *94%*	SS	*6-32* *28/5"*	15.2		
43A	3/3 *100%*	SS	*60/3"*	15.4		
44A	13/14 *93%*	SS	*28-47* *15/2"*	16.7		
45A	16/17 *94%*	SS	*31-33* *27/5"*	13.6		
46A	12/15 *80%*	SS	*20-38* *22/3"*	15.3		
47A	18/18 *100%*	SS	*3-11* *17* N=28	13.9		5.62 B
48A	17/18 *94%*	SS	*5-10* *14* N=24	14.9		5.24 BSh

Depth ft. BGS: 62, 64, 66, 68, 70, 72, 74, 76, 78, 80

Lithologic Description

Olive gray (5Y4/2) with 15% dark gray (N4/1) mottles, slightly moist, firm, silty CLAY with slight trace sand and gravel.

[Continued from previous page]

Light olive gray (5Y5/2), very moist, very soft, sandy CLAY with slight trace gravel.

Light olive gray (5Y5/2) with 10% greenish gray (5GY5/1) mottles, slightly moist, firm, silty CLAY with trace sand and slight trace gravel.

Greenish gray (10Y5/1) with 10% olive gray (5Y4/2) mottles, slightly moist, firm, silty CLAY with slight trace sand and gravel.

Greenish gray (10G5/1) with 5% dark yellowish brown (10YR4/6) mottles, moist, dense, SILT with slight trace sand.

Dark greenish gray (10GY4/1), slightly moist, very hard, clayey SILT with trace sand and slight trace gravel.

Dark greenish gray (10GY4/1), wet, very dense, silty, medium- to coarse-grained SAND with slight trace gravel.

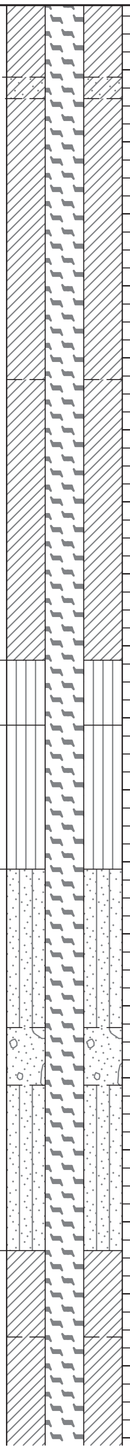
Dark greenish gray (10GY4/1), wet, very dense, silty, coarse-grained SAND and gravel.

Dark gray (10YR4/1), wet, very dense, silty, medium- to coarse-grained SAND with slight trace gravel.

Dark gray (N4/1), moist, firm, silty CLAY with slight trace sand and gravel.

Dark gray (N4/1), slightly moist, firm, silty CLAY with slight trace sand and gravel.

Borehole Detail



Elevation ft. MSL: 482, 480, 478, 476, 474, 472, 470, 468, 466, 464

Remarks

NOTE(S): Borehole abandoned using bentonite grout.

FIELD BORING LOG

CLIENT: AEG Newton Power Station
Site: Gypsum Management Facility
Location: Newton, Jasper Co., IL
Project: 07E0150A 3000
DATES: Start: 5/12/2009
Finish: 5/14/2009
WEATHER: Sunny, warm, windy, (mid-60's)

CONTRACTOR: Skinner Limited
Rig mfg/model: CME-550 ATV Drill
Drilling Method: 4¼" hollow stem auger w/split spoon sampler
FIELD STAFF: Driller: T. Skinner
Helper: T. Skinner/J. Austin
Eng/Geo: S. Suzanna Simpson

HANSON

BOREHOLE ID: B48
Well ID: n/a
Surface Elev: 542.9 ft. MSL
Completion: 103.5 ft. BGS
Station: 9,703.88N
5,042.40E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 23, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = 10.00 - during drilling
▼ =
▽ =

SAMPLE Number	Recov / Total (in) *% Recovery*	Type	*Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft³)	Qu (tsf) *Qp (tsf)* Failure Type
49A	24/24 *100%*	SS	*5-7* *12-14* N=19	15.5		5.04 BSh
50A	18/18 *100%*	SS	*4-8* *10* N=18	15.4		5.24 BSh
51A	18/18 *100%*	SS	*4-9* *10* N=19	15.7		5.04 B
52-1 52-2 52-3	18/18 *100%*	SH		14.3		
53A	24/24 *100%*	SS	*9-12* *21-26* N=33	13.9		6.21 B
54A	18/18 *100%*	SS	*6-11* *17* N=28	13.8		6.79 Sh
55A	24/24 *100%*	SS	*6-12* *15-24* N=27	13.6		7.37 Sh
56A	18/18 *100%*	SS	*5-8* *12* N=20	13.9		3.88 Sh
57A	18/18 *100%*	SS	*5-12* *19* N=31	13.4		6.21 Sh
58A 58B	24/24 *100%*	SS	*4-18* *20-22* N=38	12.5 13.4		5.82 BSh
59A 59B	16/16 *100%*	SS	*16-33* *27/4"*	16.0 15.7		3.69 Sh
60A 60B	18/18 *100%*	SS	*16-21* *15* N=36	12.6		

Depth ft. BGS: 82, 84, 86, 88, 90, 92, 94, 96, 98, 100

Elevation ft. MSL: 462, 460, 458, 456, 454, 452, 450, 448, 446, 444

Lithologic Description:

Dark gray (N4/1), slightly moist, firm, silty CLAY with slight trace sand and gravel.
[Continued from previous page]

Dark gray (N4/1), slightly moist, hard, silty CLAY with slight trace sand and gravel.

Dark gray (N4/1), slightly moist, firm, silty CLAY with slight trace sand and gravel.

Dark gray (N4/1), very moist, dense, silty, fine- to coarse-grained SAND with slight trace gravel.

Dark gray (N4/1), slightly moist, hard, silty CLAY with slight trace sand and gravel.

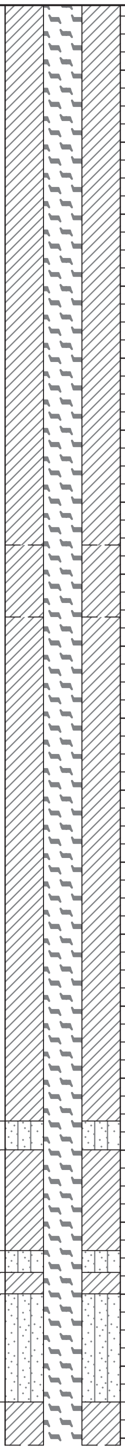
Dark gray (N4/1), wet, dense, silty, fine- to medium-grained SAND with slight trace gravel.

Dark gray (N4/1), slightly moist, hard, silty CLAY with slight trace sand and gravel.

Dark gray (N4/1), wet, dense, silty, very fine- to medium-grained SAND with slight trace gravel.

Dark gray (N4/1), slightly moist, hard, silty CLAY with slight trace sand and gravel.

Borehole Detail



Remarks

NOTE(S): Borehole abandoned using bentonite grout.

FIELD BORING LOG

CLIENT: AEG Newton Power Station
Site: Gypsum Management Facility
Location: Newton, Jasper Co., IL
Project: 07E0150A 3000
DATES: Start: 5/12/2009
Finish: 5/14/2009
WEATHER: Sunny, warm, windy, (mid-60's)

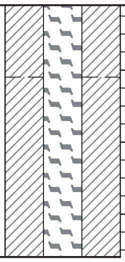
CONTRACTOR: Skinner Limited
Rig mfg/model: CME-550 ATV Drill
Drilling Method: 4¼" hollow stem auger w/split spoon sampler
FIELD STAFF: Driller: T. Skinner
Helper: T. Skinner/J. Austin
Eng/Geo: S. Suzanna Simpson

BOREHOLE ID: B48
Well ID: n/a
Surface Elev: 542.9 ft. MSL
Completion: 103.5 ft. BGS
Station: 9,703.88N
5,042.40E

TOPOGRAPHIC MAP INFORMATION:
Quadrangle: Latona
Township: North Muddy
Section 23, **Tier** 6N; **Range** 8E

WATER LEVEL INFORMATION:
▼ = 10.00 - during drilling
▼ =
▽ =

SAMPLE			TESTING								
Number	Recov / Total (in) *% Recovery*	Type	*Blows / 6 in* N - Value **RQD**	Moisture (%)	Dry Den. (lb/ft³)	Qu (tsf) *Qp (tsf)* Failure Type	Depth ft. BGS	Lithologic Description	Borehole Detail	Elevation ft. MSL	Remarks
61A	24/24 *100%*	SS	*7-12* *18-25* N=30	13.4		6.59 Sh		Dark gray (N4/1), slightly moist, firm, silty CLAY with slight trace sand and gravel.		442	
62A	17/18 *94%*	SS	*12-18* *22* N=40	15.3		3.88 BSh	102	Dark gray (N4/1), slightly moist, hard, silty CLAY with slight trace sand and gravel.		440	



EOB = 103.5 feet bgs

NOTE(S): Borehole abandoned using bentonite grout.

CIPS NEWTON POWER STATION	BORING G-106		SHEET 1 of 1
DATE STARTED 8/1/90	DATE COMPLETED 8/1/90	LOGGED BY RAB	SURFACE EL. 529.0
DRILLING CONTRACTOR: BROTCKE ENG.		DRILL METHOD: H.S. AUGER	

Depth (ft)	N-Value	SOIL/ROCK DESCRIPTION	VAPOR CONCENTRATION (ppm) 10^0 10^1 10^2 10^3	COMMENTS	Depth (ft)
0	22	Brn. clayey SILT, tr. roots, blocky, dry.			0
	20 18	Brn. sandy silty CLAY, tr. pebbles, sl. moist, blocky.			
	33	Mottled gray & brn. silty sandy CLAY, tr. pebbles, moist.			
10	50 72	Brn. sandy CLAY, tr. pebbles, vert. med. sand filled fract., so. mn & iron oxid., moist.			10
	50	Brn. coarse SAND.			
20	80 43 59 45	Gray brn. sandy silty CLAY, tr. pebbles, coal frag., oxid. vert. fract., hard.			20
	9	Gray coarse – v. coarse SAND.		∇	
	63	Gray sandy silty CLAY, tr. pebbles, moist.			
30		Coarse – v. coarse SAND grading downward to gravel.			30
	39 33	Gray sandy silty CLAY, tr. pebbles, unweathered.			
		End of Boring = 36.0'			
40					40

SOIL/ROCK BORING DATA

HANSON ENGINEERS INCORPORATED

PAC REVIEWED 11-19-90 DATE

RKC APPROVED 11-19-90 DATE

CIPS
NEWTON POWER STATION
NEWTON, ILLINOIS

JOB NO. 89S5008A

RAPPS

BORING LOG

ENGINEERING and APPLIED SCIENCE

2387 WEST MONROE - SPRINGFIELD IL 62704 - (217)787-2118

Client: CIPS–NEWTON
Project: WELL INSTALLATION
Boring No: G202
Drilling Firm: PROFESSIONAL SERVICE IND.
Drilling Method: 4–1/4 ID HSA
Surface Elev. 537.24
Logged By: MSS
Checked By:
Date Started: 10–16–96
Completed: 10–16–96

DEPTH	Material Description Classification System UNIFIED	Sampling Tube No.	Sampling Type	Sampling % Rec.	Tests OVM (ppm)	Tests Qu t/sf PEN	Tests Moist	Comments	Well	DEPTH
0	Fill Material: Drilled through built drilling pad	1	5.0' CME continuous sampler	0		NA	NA			0
5	10.0	2		0		NA	NA			5
10	Brown–gray silty SAND (SM) w/clay & trace pebbles 12.5 Brown–clayey SILT (ML) w/ sand & pebbles	3		30		NA 0.25 NA	moist wet			10
15	16.5 Gray silty CLAY (ML–CL) w/pebbles 18.0 Brown coarse SAND (SM) w/silt 20.8	4		30		NA NA NA NA	moist moist	Very weathered		15
20	Gray silty CLAY (ML–CL) w/pebbles	5		60		4.5+ 4.5+ 4.5+	dry			20
25		6		100		4.5+ 4.5+ 4.5+ 4.5+	moist moist			25
30										30

Water Level NA of NA hrs.
Water Level NA of NA hrs.

N 6649.68, E 6587.20

Sheet 1 of 3

RAPPS

BORING LOG

ENGINEERING and APPLIED SCIENCE

2387 WEST MONROE - SPRINGFIELD IL 62704 - (217)787-2118

Client: CIPS-NEWTON
Project: WELL INSTALLATION
Boring No: G202
Drilling Firm: PROFESSIONAL SERVICE IND.
Drilling Method: 4-1/4 ID HSA
Surface Elev. 537.24
Logged By: MSS
Checked By:
Date Started: 10-8-96
Completed: 10-8-96

DEPTH	Material Description Classification System UNIFIED	Sampling Tube No.	Sampling Type	Sampling % Rec.	Tests OVM (ppm)	Tests Qu t/sf PEN	Tests Moist	Comments	Well	DEPTH
30	Gray silty CLAY (ML-CL) w/pebbles 31.3	7	5.0' CME continuous sampler	100		4.5+	moist			30
	Brownish Gray CLAY (CH) w/silt 32.3					4.5+				
	Gray silty CLAY (ML-CL) w/pebbles					3.0	wet			
						4.5+	moist			
	36.0					4.5+				
35	Gray silty SAND (SM) 36.5	8		100		4.5+				35
						NA	wet			
						4.5+	moist			
						4.5+				
						4.5+				
40	Gray silty CLAY (ML-CL) w/pebbles	9		90		4.5+	moist			40
						4.5+				
						4.5+	moist			
						4.5+				
						4.5+				
45		10		100		4.5+	moist			45
						3.75				
						4.5+	moist			
						4.5+				
						4.5+				
50		11		100		4.5+	moist			50
						4.5+				
						4.5+	moist			
						4.5+				
						4.5+				
55		12		100		4.5+	moist			55
						4.5+				
						4.5+	moist			
						4.5+				
60						4.5+				60

Water Level NA of NA hrs.
Water Level NA of NA hrs.

N 6649.68, E 6587.20

Sheet 2 of 3

RAPPS

BORING LOG

ENGINEERING and APPLIED SCIENCE
2387 WEST MONROE - SPRINGFIELD IL 62704 - (217)787-2118

Client: CIPS-NEWTON
Project: WELL INSTALLATION
Boring No: G202
Drilling Firm: PROFESSIONAL SERVICE IND.
Drilling Method: 4-1/4 ID HSA
Surface Elev. 537.24
Logged By: MSS
Checked By:
Date Started: 10-16-96
Completed: 10-16-96

Classification System UNIFIED

DEPTH	Material Description	Sampling: Tube No.	Sampling: Type	Sampling: % Rec.	Tests: OVM (ppm)	Tests: Qu t/sf PEN	Tests: Moist	Comments	Well	DEPTH
60	Gray silty CLAY (ML-CL) w/pebbles 61.4	13	5.0' CME continuous sampler	100		4.5+				60
	Gray GRAVEL (GM) w/silt 62.0					4.5+	wet			
	Gray silty CLAY (ML-CL) w/pebbles					4.5+				
						4.5+	wet			
						4.5+				
65		14		100		4.5+				65
						4.5+	wet			
						4.5+	wet			
						4.5+				
	69.5 Gray fine sandy SILT (SM)					NA		Blind drill: Augers plugged w/SILT-SAND		
70	End Of Boring @70.0'									70
75										75
80										80
85										85
90										90

Water Level NA of NA hrs.
Water Level NA of NA hrs.

N 6649.68, E 6587.20

Sheet 3 of 3

RAPPS

BORING LOG

ENGINEERING and APPLIED SCIENCE

2387 WEST MONROE - SPRINGFIELD IL 62704 - (217)787-2118

Client: CIPS-NEWTON
Project: WELL INSTALLATION
Boring No: G203
Drilling Firm: PROFESSIONAL SERVICE IND.
Drilling Method: 4-1/4 ID HSA
Surface Elev. 530.97
Logged By: MSS
Checked By:
Date Started: 10-15-96
Completed: 10-15-96

DEPTH	Material Description Classification System UNIFIED	Sampling Tube No.	Sampling Type	Sampling % Rec.	Tests OVM (ppm)	Tests Qu t/sf PEN	Tests Moist	Comments	Well	DEPTH
0	Tan, mottled reddish clayey SILT (MH) 3.5 Gray, mottled brown silty CLAY (MH-CH) w/trace coarse sand & pebbles	1	5.0' CME continuous sampler	75		4.5+ 4.5+ 4.0 2.75	dry moist	Very soft		0
5		2		100		1.75 1.0 0.75 1.75 2.5	moist moist			5
10	11.5 Brown silty clay (CL-ML) w/coarse sand & pebbles	3		60		NA NA 2.5 2.75	dry dry			10
15		4		70		NA NA NA NA	dry dry			15
20	21.5 Brown SAND (SM) w/silt, poorly sorted 23.0 Gray, mottled brown silty CLAY (CL) w/pebbles	5		70		4.0 4.0 NA 4.5+	dry dry			20
25	28.0 Gray silty CLAY (CL-ML) w/pebbles	6		95		4.5+ 4.5+ 4.25 4.5 4.5+	moist dry			25
30										30

Water Level NA of NA hrs.
Water Level NA of NA hrs.

N 5821.29, E 6113.10

Sheet 1 of 3

RAPPS

ENGINEERING and APPLIED SCIENCE

BORING LOG

2387 WEST MONROE - SPRINGFIELD IL 62704 - (217)787-2118

Client: CIPS-NEWTON **Project:** WELL INSTALLATION **Boring No:** G203

Drilling Firm: PROFESSIONAL SERVICE IND. **Drilling Method:** 4-1/4 ID HSA **Surface Elev.** 530.97

Logged By: MSS **Checked By:** **Date Started:** 10-15-96 **Completed:** 10-15-96

Classification System UNIFIED

DEPTH	Material Description	Sampling: Tube No.	Sampling: Type	Sampling: % Rec.	Tests: OVM (ppm)	Tests: Qu t/sf PEN	Tests: Moist	Comments	Well	DEPTH
30	Gray silty CLAY (ML-CL) w/pebbles 33.2 Gray fine grain SAND (SM) w/silt 34.5	7	5.0' CME continuous sampler	100		4.5+ 4.5+ 4.5+ 4.5	dry dry			30
35	Brownish gray silty CLAY (CL) w/pebbles 36.5	8		100		4.0 4.5 4.5+ 4.5	dry dry			35
40	Gray silty CLAY (ML-CL) w/pebbles	9		100		4.5+ 4.5+ 4.5+ 4.5+	dry dry			40
45		10		100		4.5+ 4.5+ 4.5+ 4.5+	dry dry			45
50		11		100		4.5+ 4.5+ 4.5+ 4.5+ 4.5+	moist moist			50
55	57.5 Gray fine SAND (SM) w/silt 58.0 Gray silty CLAY (ML-CL) w/pebbles	12		100		4.5+ 4.5+ 4.5+ 4.5+ 4.5+	moist moist			55
60										60

Water Level NA of NA hrs.
Water Level NA of NA hrs.

N 5821.29, E 6113.10

Sheet 2 of 3

RAPPS

BORING LOG

ENGINEERING and APPLIED SCIENCE

2387 WEST MONROE - SPRINGFIELD IL 62704 - (217)787-2118

Client: CIPS-NEWTON **Project:** WELL INSTALLATION **Boring No:** G203
Drilling Firm: PROFESSIONAL SERVICE IND. **Drilling Method:** 4-1/4 ID HSA **Surface Elev.** 530.97
Logged By: MSS **Checked By:** **Date Started:** 10-15-96 **Completed:** 10-15-96

DEPTH	Material Description Classification System UNIFIED	Sampling			Tests			Comments	Well	DEPTH
		Tube No.	Type	% Rec.	OVM (ppm)	Qu t/sf PEN	Moist			
60	Gray silty CLAY (ML-CL) w/pebbles		5.0' CME continuous sampler			4.5+				60
						4.5+	moist			
		13		100		4.0				
						4.5	moist			
						4.5+				
65	65.6									65
	Gray fine SAND (SM) w/silt 66.4					3.0	wet			
	Gray fine SAND-SILT (SM) w/trace gravel	14		80		4.0	wet			
						NA				
70	70.0									70
	Blind Drill: Auger plugged & redrilled to 73.0'									
	End Of Boring @73.0'									
75										75
80										80
85										85
90										90

Water Level NA of NA hrs.
Water Level NA of NA hrs.

N 5821.29, E 6113.10

Sheet 3 of 3