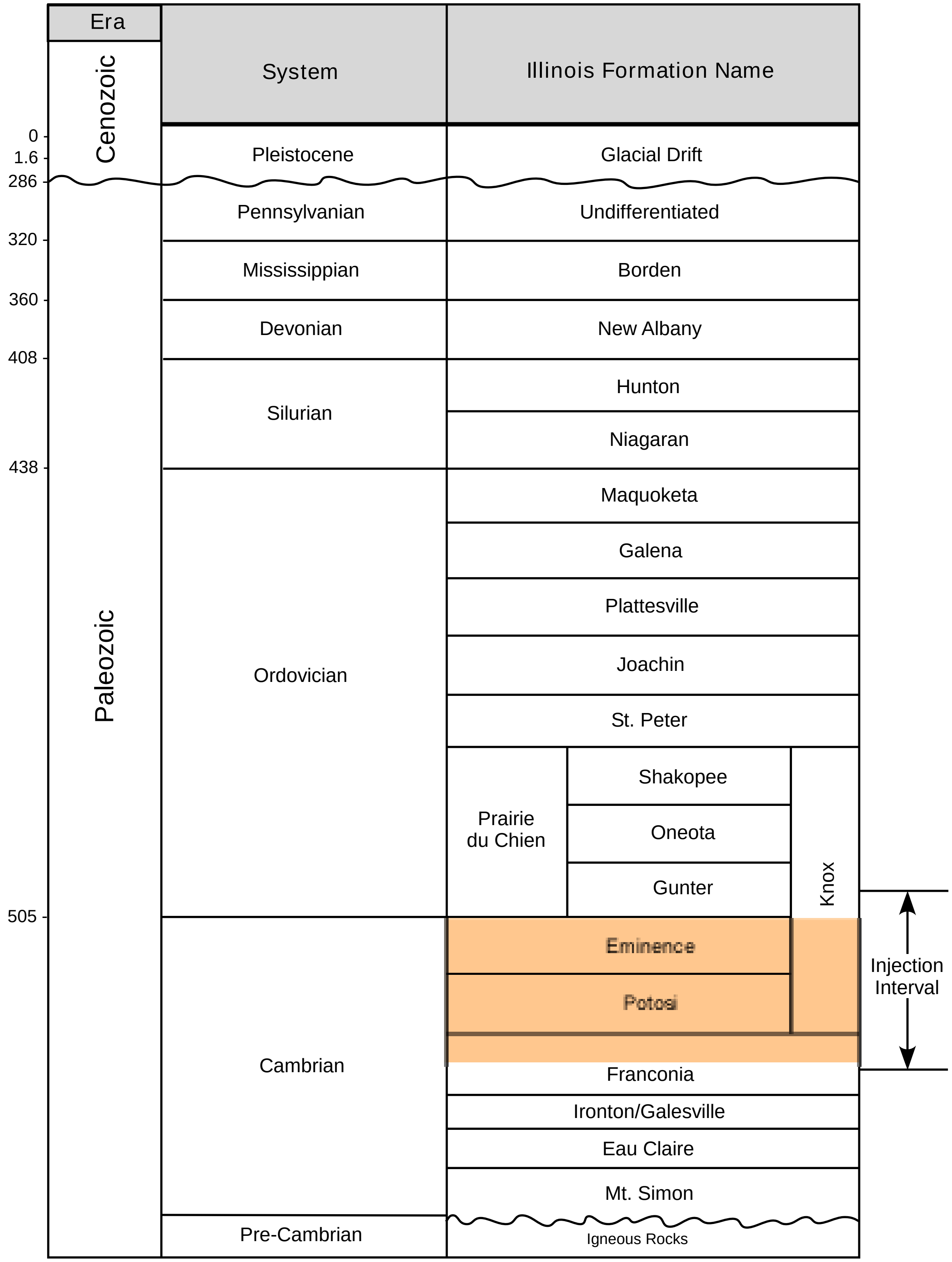

adapted from: Nieto, 1990; Petroleum Frontiers VOl 4. No. 4, 1988
recreated by: PWP Sandia 9/23/2008

Figure 2-1 Stratigraphic Column of Cabot Corporation

2.4.1.1 Bedrock Aquifers

In Douglas County, limited quantities of fresh water are obtained from bedrock aquifers. Pennsylvanian bedrock underlies the glacial drift in most of the county (Kolata, 2005). Although the Pennsylvanian is mostly shale, thin beds of limestone and sandstones are also found interbedded which might provide a limited local source of fresh water. Along the anticlinal belt where bedrock lies near the surface, fractured dolomites of Silurian and Devonian age also provide acceptable levels of drinking water.

2.4.1.2 Sand and Gravel Aquifers

2.4.1.2.1 Banner Formation Aquifer

The Banner Formation of east-central Illinois includes a thick, extensive sand member, the Mahomet Sand Member. This member is a valley train deposit which may be over 150 feet thick and is composed of clean sand, gravel, and minor amounts of silt and clay (Kempton, et al., 1982). The deposit grades upward into sands and silts with water yields greatly reduced along valley margins, where thicknesses may be 50 feet or less. In DeWitt County, municipal and industrial water supplies are obtained from the Mahomet. Figure 2-35 includes cross-sections showing the sand and gravel aquifers in the area.

2.4.1.2.2 Glasford Formation Aquifer

The main member of the Glasford Formation is the base of the Vandalia Till. At shallower depths, an aquifer can be found between the Radnor and Vandalia Till Members (see Figures 2-35). Thicknesses of the Glasford Aquifer in the east-central portion of the state range from 5 feet to over 60 feet. It is believed that areas of greater thicknesses may be the result of two units overlying each other. In Douglas County, the Glasford is an important aquifer with distribution and thickness less predictable than the Banner Formation.

2.4.1.2.3 Wedron Formation Aquifer

The principal aquifer of the Wedron Formation is the Ashmore Aquifer consisting of an outwash sand and gravel averaging 10 feet in thickness. At some sites, thicknesses of 50 feet have been reported. In the northeast corner of the state, the Wedron is well developed, and small municipal supplies of water are obtained.

2.4.1.2.4 Surficial Aquifers

The Henry Formation consists of surficial sand and gravel found as narrow deposits with thicknesses that may range from a few feet to as much as 50 feet. The formation is more developed and thickest along river valleys, and successful wells are relatively shallow.

2.4.2 Local Hydrogeology

2.4.2.1 Bedrock Aquifer

The bedrock formations of the Tuscola area are comprised of limestones, dolomites, sandstones, and shales. These formations are not recognized as major aquifers due to their high TDS levels; unless they are found near the surface and fracturing is sufficient to produce large quantities of fresh water. For over 50 years, the city of Tuscola utilized wells completed in the Silurian dolomite for public water supply. These wells were typically openhole completions in the Niagaran Formation at depths below 400 feet. The well yields from these wells were generally less than 200 gallons per minute with varying water level drawdowns of 40 to 100 feet in specific wells (ISGS, 1950). Approximately 3 miles east of the Cabot site, Devonian and Silurian rocks are found near the surface on the Tuscola Anticline (Figure 2-36). The deepest water producing well on record in the area was completed in 1897, at a depth of 3,017 feet, and was located in the western portion of Tuscola, 2,075 feet FNL and 750 feet FWL of Section 34, T6N R8E. This location is apparently 13,250 feet from Cabot Injection Well No. 2 (~2.51 miles) and outside the Area of Review (AOR). Originally, the well was to be completed in the Mt. Simon Formation, but it is doubtful that the Mt. Simon was ever reached. Unfortunately, only a partial drillers log was available, and it is not known what formation the well was completed in. Analysis of a water sample taken from the well reported 139 parts per million (ppm) hardness, 964 ppm mineral content, and 1.6 ppm iron content. The well was capable of producing 50 gallons per minute (gpm), and its use was discontinued in 1916. The well was plugged and abandoned in 1951, by filling the hole with gravel from TD to 50 feet, and filling the top 50 feet with grout (John S. Nealon, ISWS, written communication, 1986). The location of this well is reportedly beneath a building currently housing an antique business.

Water bearing formations deeper than the Silurian increase in TDS values with depth. Figure 2-37 includes isoconcentration maps of brines in the Ordovician "Trenton" (Kimmswick, Galena) and St. Peter Formations.

LIST OF APPENDICES

Whittaker, S., 1988, Silurian pinacle reef distribution in Illinois: Model for hydrocarbon exploration: Ill. State Geological Survey, Ill. Petroleum 130, 32 p.

Willman, H. B. and Buschbach, T. C., 1975, Ordovician System, in Handbook of Illinois Stratigraphy: Illinois State Geological Survey Bulletin 95, p. 47-87.

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Hanson, R., 1950, Public Ground-Water in Illinois, Division of the Water Survey Bulletin No. 40, Urbana, IL.

Hydropoll, Inc., 1991, Assessment Of Fourth Quarterly (Annual 1991) Collected Groundwater Samples, Closed RCRA Impoundment, Cabot Corporation Plant, Tuscola, IL., 33 p.

Kolata, D.R., 2005, Bedrock Geology of Illinois, Illinois State Geological Survey Illinois Map 14: Champaign, IL, 1:500,000.

Nelson, W.J., 1995, Structural features in Illinois, Illinois State Geological Survey Bulletin 100, Champaign, IL, 144 p.

Piskin and Bergstrom, 1975, Glacial Drift in Illinois: thickness and character, Illinois State Geological Survey Circular 490, Champaign, IL, 35 p.

Treworgy, J.D. and Whitaker, S.T., 1990, 1 O'Clock Cross Section in the Illinois Basin: Illinois State Geological Survey Open File Series, 1990-5.

APPENDIX 2-8

CABOT SHALLOW MONITORING WELL PROGRAM

ASSESSMENT OF FOURTH QUARTERLY (ANNUAL 1991) COLLECTED GROUNDWATER SAMPLES, CLOSED RCRA IMPOUNDMENT CABOT CORPORATION PLANT, TUSCOLA, IL PREPARED BY HYDROPOLL, INC. DECEMBER 1991.

No-Migration criteria set forth under the 40 Code of Federal Regulations (CFR) Part 148, 53 Federal Register 28117 (July 26, 1988). Where new information is available, it has been incorporated into this section, with a discussion of its potential impact on the original determination detailed.

This section contains a general discussion of the accepted and current knowledge about the evolution of the Illinois Basin, the general stratigraphy of the region of interest - east-central Illinois, and the setting of this region within the structural framework of the Illinois Basin. The regional area of interest, for purposes of this Petition Reissuance request, is defined as an area 45 miles in radius centered on the Cabot facility and its injection system. This area of interest was selected originally in the 1990 Cabot Petition, as part of a geological report characterizing the Tuscola area, prepared by Dr. Albert S. Nieto, Consultant, and Cabot has maintained and utilized these geological results for the current Petition Reissuance and Renewal document.

The Cabot Tuscola site is underlain by gently dipping, unfaulted and continuous sedimentary rock units. General geological knowledge and site-specific information, downhole geophysical logging, drill cuttings examination, x-ray diffraction of shale samples, completion and recompletion well data, etc., all demonstrate that the sedimentary rock units, at the level of the injection formations, members, and individual beds in this region of interest are laterally continuous. The sedimentary interval of interest is defined as the section from the bottom of the lowermost Underground Source of Drinking Water (USDW) (Silurian Moccasin Springs) to the base of the Injection Zone (Potosi, Franconia Dolomites). The injection system is favorably located on the east flank of a small anticlinal structure which limits any less dense fluids (lighter than the native formation brines) to migrate northwesterly in the opposite direction to the Tuscola Anticline. Additionally, included within this section are discussions of in-situ stresses and the regional and local seismicity of the area.

shale intercalations. The Gunter Formation can be considered the lowermost of these intercalations. The Oneota ranges in thickness from 100 feet in the north to slightly over 300 feet in the regional area. The Oneota represents the containment interval and immediate confining section for this demonstration.

Shakopee Dolomite

Pre-St. Peter Formation solution effects and erosional activity has removed extensive portions from the top of the Shakopee Dolomite in the northern part of the state. However, in east-central Illinois, the Shakopee Dolomite varies in thickness only slightly, thickening regularly to the southeast with observed variation in thickness approximately 100 feet in 50 miles. The virtual constancy of thickness of the relevant sedimentary sequence for this demonstration event (Mississippian to Cambrian), even in the presence of a major erosional event (Pre-Tippecanoe), will be discussed later in this demonstration as an aide to structural mapping.

Lithologically, the Shakopee Dolomite varies from argillaceous (clayey) to pure dolomite with thin interbeds of sandstone, shale, and siltstone. The Shakopee is designated the Confining Interval here, with interbeds of sandstone and shale being considered as very favorable characteristics for containment in this injection system. The shales act as direct barriers to flow, and the sands behave as pressure relief dissipaters. Although no specific hydraulic conductivity data is present, the sands due to their favorable reservoir properties can store large volumes of fluid and hold pressure as a relief reservoir.

Ancell Group

The next shallowest overlying rock group is the Tippecanoe Sequence which begins with the St. Peter Sandstone and includes the rest of the Ordovician, all the Silurian, and the Lower Devonian. In the regional area, the Ordovician portion of the Tippecanoe is composed of the Ancell Group (St. Peter and Joachim Formations), the Platteville Group, and the Galena Group.

The St. Peter Sandstone was deposited on the erosional surface on top of the Shakopee Dolomite (top of Prairie du Chien) in the area. The thickness of the St. Peter Sandstone varies moderately (from 150 feet to 200 feet) in the region, due to minor relief on the Shakopee erosional surface (Illinois Chamber of Commerce Docket No. 46678, 1960, p. 29). The upper half of the St. Peter

2.2.3 Formations Above the Lowermost USDW

The contact between the Devonian and Mississippian Systems is conformable nearly everywhere in Illinois and occurs within shales of the New Albany Group. Many structural features were formed or reactivated at the close of the Mississippian Era. Uplifted areas underwent subsequent erosion, and a major unconformity is found to separate the Mississippian and Pennsylvanian Systems. Only Lower Mississippian strata are present in the region consisting of a few tens of feet of dolomitic limestone (Kinderhookian) and approximately 500 feet of thick, argillaceous, slightly calcareous, glauconitic, fine-grained siltstone with lesser amounts of silty shale (Borden siltstone).

Pennsylvanian rocks form the bedrock surface for most of Illinois (Kolata, 2005). This surface has been eroded as a result of the Late Paleozoic deformation and further eroded during the Pleistocene glaciation. Pennsylvanian rocks characteristics include many vertical changes in lithology, some frequently abrupt, which can produce many laterally extensive sandstones, siltstones, coal-seams, underclays, and shales.

The balance of subsurface formation materials in the region are sediments of Quaternary age, ranging in thickness from less than 50 feet to more than 400 feet and consist of Pleistocene glacial drift and various types of Holocene soils (Piskin, 1975).

Thickness Variation of Mississippian/Cambrian Sequence

Table 2-1 shows the depths (depths in Column 1) of the Rosiclare and the thickness of sedimentary rock between it and the top of the Shakopee, Oneota, and Eminence formations based on four deep-wells with modern well logs in a one-mile radius around the Cabot Tuscola site. This Mississippian/Cambrian sequence represents the containment, confinement, and secondary confinement interval for the Cabot Tuscola Petition Demonstration. The maximum difference in elevation is 35 feet of structural relief between formation tops of the Rosiclare Formation, with maximum variation in thickness of 45 feet between the Rosiclare and the Eminence. From Table 2-1, the maximum thickness variation observed between the wells is only 1.5% of the total thickness. This indicates that although several important unconformities exist within the sedimentary section, there remains remarkable consistency and conformity in the

Borden Formation

The Borden Formation is approximately 616 feet thick. It is described as grey to grayish green, very silty calcareous shale, with small amounts of light brown to brown shale. It is friable, carbonaceous, pyritic, with fine sandy lenses near the base of the unit.

St. Louis/Salem Formation

The St. Louis Formation is approximately 196 feet thick. It is described as brown to light brown, very finely crystalline, dense, sandy dolomite, carbonaceous and pyretic with occasional thin grey-green shale lenses, and the unit tends to be limey in the lower half.

St. Genevieve Formation

The St. Genevieve Formation is approximately 85 feet thick. It is described as brown to light brown, with traces of grey, cryptocrystalline limestone. The lower half of the unit is very sandy, with very fine to fine, clear to frosted sand grains.

Pennsylvanian, undifferentiated

The Pennsylvanian is approximately 1,400 feet thick. It is described as alternating limestones, sandstones, dolomites, and siltstone units, with lesser thicknesses of shale.

A limited supply of water can sometimes be obtained from these thin stringers when water cannot be obtained directly from overlying glacial till deposits. Sands and creviced limestones, such as the Pennsylvanian Mattoon Formation, may also yield small quantities of water.

Glacial sand and gravel deposit fill in the eroded bedrock valleys may provide excellent aquifers throughout east-central Illinois (Kolata, 2005). The Pesotum Valley is located north of the Cabot site, however, no prolific aquifers are reported. Glacial till also provides a limited source of water for residential and farm use in the area, with wells completed in till deposits from sand lenses averaging only 5 feet to 10 feet in thickness.

2.4 HYDROGEOLOGY

2.4.1 Regional Hydrogeology

The bedrock of east-central Illinois has limited potential for providing acceptable levels of drinking water (Hanson, 1950). Only where the bedrock is at or near the surface can water with acceptable TDS quality levels can be found. Normally below depths of 200 to 400 feet, the water becomes too highly mineralized for public usage. Along the trace of the La Salle Anticlinal Belt (Nelson, 1995), older more permeable rocks can be found near the surface and are capable of producing water of good quality. However, quality quickly deteriorates with depth. Figure 2-34 is a north-south and northwest-southeast cross-section of the state showing TDS values of formation waters. Unfortunately, water from the shallow bedrock is usually only available in small quantities, where fractured limestone and permeable sandstone is encountered. Since most of the bedrock surface in east-central Illinois (Kolata, 2005) is found at depths that contain highly mineralized water, an alternate water supply is needed. Groundwater localized within glacial deposits, which lie on top of the bedrock, provide the bulk of water supplies for farms and residences in the Tuscola area. The hydraulic conductivity of glacial aquifers is highly variable in shallow deposits, but tends to increase and become less variable with depth (Kempton et. al., 1982). Groundwater movement within glacial deposits and the underlying bedrock is very slow (Piskin and Bergstrom, 1975). A shallow monitoring well program at the Cabot plant determined that regional groundwater flow in the glacial till deposits is to the south-southeast. A copy of the shallow monitoring well program is included as Appendix 2-8, and represents the historical monitoring program, which has evolved with some of the original monitor wells plugged. Presently the current program uses a limited number (6 site monitor wells) to monitor a horizon at 60-feet. A description of the current program is described below:

> The shallow monitoring well program data is taken from: *Assessment of Fourth Quarterly (Annual 1991) Collected Groundwater Samples, Closed RCRA Impoundment, Cabot Corporation Plant, Tuscola, IL,* prepared by Hydropoll, Inc. in December 1991. A total of 25 wells are present on the plant grounds. Of this total, 19 are included in the monitoring system for the closed impoundment as approved by the Illinois Environmental Protection Agency. Nine wells are

completed in the weathered till at depths of 20 to 30 feet, five wells are completed in a deeper sand unit in the till at approximately 100 feet, four wells are completed in the till at depths of 50 to 75 feet, and one deeper well drilled to a depth of 212 feet and screened in a silt from 199 to 203 feet. Four wells of the 19 total are located singly and 15 are located in multiple well clusters. One of the clusters is located upgradient and the remaining five clusters is located down gradient of the closed impoundment

Potentiometric maps were constructed from the water level data in the weathered till and in the deeper sand unit. The potentiometric surface map of the shallow groundwater showed the direction of the regional groundwater flow. The regional flow is to the southeast. A groundwater divide, across which no flow occurs, is located just north of the closed impoundment. The divide prevents flow of groundwater from the closed impoundment. The calculated field hydraulic conductivity in the shallow weathered till was 62,1 ft/year. Effective porosity of the weathered till is estimated to be 0.10. A groundwater velocity of 4.0 ft/yr was calculated using these values.

Water levels in the deep sand did not vary significantly between the wells. A water level difference of only 0.57 feet was measured between the wells. The water flow direction within the deeper sand was tentatively determined to be to the west. Field hydraulic conductivity was determined as 3400 ft/yr. Effective porosity of the deep sand is estimated as 0.20. A groundwater velocity of 42.5 ft/yr was calculated using these values.

Water level differences in the well clusters indicated that the groundwater moves downward between the shallow till wells and the deep sand wells in the same cluster.

Prior to the continental glaciers, erosion had altered the bedrock surface. Well developed drainage patterns resulted in the region. Afterwards, glaciers deposited debris across the bedrock surface. Glacial debris such as sand, gravel, and boulders are important bedrock valley fill for potential sources of large groundwater supplies in the state.

Glacial deposits of east-central Illinois are assigned to three stages of continental glaciation, Kansan, Illinoian, and Wisconsin (Piskin and Bergstrom, 1975). Three formations evolved from each period: the Banner, Glasford, and Wedron. Each of these formations has several members composed of glacial tills, outwash, or a combination of both. Glacial deposits covering the bedrock surface in this region may range from a few feet to more than 400 feet.

stratigraphic thickness between the top and bottom of the sedimentary package in the area around the Cabot Tuscola site. Because only a small amount of structural relief (35 feet) is present in this area and is nearly the same as the maximum difference in thickness (45 feet), it is not possible to make inferences about detailed structural features in deep units with any degree of confidence (given the limited number of wells present). However, the constancy in thickness offers an aid to structural mapping of deeper units, by incorporating the widespread subsurface control of a shallower unit (Rosiclare) to evaluate and infer overall deeper seated structural features surrounding the area of the Cabot Tuscola site.

Only very slight and regular variation in thickness at the area of the Cabot Tuscola site is present (see Figures 2-2, 2-4, 2-6, and 2-7) as indicated in isopach maps of the major geologic systems (Cambrian, Ordovician, Silurian, Devonian, and Mississippian) as well as of the Shakopee Formation (Figure 2-5).

3.1.1 Regional Structural Geology

Figure 2-8 consists of a map of the north-central United States showing the extent of the Illinois Basin and surrounding major structural features (Collinson et al., 1988). Figure 2-9 details the major structural features within the Illinois Basin. The structure on top of the Trenton (Galena) or equivalent in the Illinois, Michigan, and Forest City basins is presented in Figure 2-10. The structure on top of the Prairie du Chen Group is presented in Figure 2-11. The Illinois Basin is closed to the south by the Pascola Arch (not shown in the figure because it lies under the Mesozoic sediments of the Mississippi Embayment). The Pascola Arch is a major structural high between the Ozark Uplift and the Nashville Dome. The Pascola Arch is a relatively recent feature, because as indicated previously, stratigraphic evidence shows that the Illinois Basin was an open trough to the south during most of Paleozoic time. The time when the Pascola Arch developed is not certain but it is quite probably rather late in Paleozoic time. This represents the time that marks the beginning of the major tectonic activity responsible for all of the structural features within the basin. Figure 2-12 includes north-south and east-west cross-sections of the Illinois Basin (Collinson et al., 1988). The cross sections indicate that the folding and faulting that affects younger sediments also equally affects the oldest sediments, providing direct evidence of the relatively late age of the major deformation (Treworgy, et al 1990).

During the Lower and Middle Paleozoic Era, the Tuscola area was part of a large shallow basin that underwent rather uniform shallow marine deposition. Cambrian deposition consisted of sandstones and dolomites with few shale occurrences, the exception being the Eau Claire Formation, which contains thin shale sequences. Lower and Middle Ordovician deposition was similar to Cambrian, except fewer sandstones were deposited. During Upper Ordovician, the Maquoketa, a thick shale sequence, was deposited over the 4,000 to 5,000 feet of previously deposited carbonates and sands. Maquoketa Shale thicknesses in the area range from 180 to 230 feet (Bristol and Prescott, 1968).

As previously stated, uplift of the La Salle Anticlinal Belt, which includes the Tuscola Anticline, began near the end of the Mississippian and continued at least through the end of the Pennsylvanian (Nelson, 1995). Figure 2-24 shows the Pre-Pleistocene bedrock surface in the Tuscola area. Silurian age units are the oldest formations exposed on the crest of the anticline. The cross sections included in Figure 2-24 agree well with Figure 2-23. The geological formations of the Cabot Injection Zone and Confining Zone are intact, and not breached across the crest of the Tuscola Anticline and the mapped area.

During the formation of the anticlinal structure, a simultaneous downwarp of the Fairfield Basin was occurring. Pennsylvanian sediments were rapidly filling the basin and, by the end of the Pennsylvanian, sediments had completely filled the basin. Uplift probably continued after Pennsylvanian time, evidenced by the Kewanee and McLeansboro Groups, which are found dipping away from the crest on both sides of the anticline (Bristol and Prescott, 1968). As discussed earlier, more than 2,500 feet of Pennsylvanian, Mississippian, and Devonian Rocks are absent from the crest of the anticline, and it is difficult to determine when anticlinal growth had terminated.

Figure 2-25 shows the distribution of the bedrock surface in Illinois. The bedrock surface of the Tuscola area is covered by unconsolidated glacial deposits of the Pleistocene Series, consisting of soils, sands, gravels, and boulders. Pleistocene sediment thickness increases on the flanks of the Tuscola anticline. This increased thickness is a result of glacial infill of two major streams that drained to the northwest. Pleistocene sediments on the crest of the anticline are up to approximately 100 feet in thickness and lie unconformably upon Silurian and Devonian age rocks. Sediment on the flanks rests on Pennsylvanian bedrock and is more than 250 feet thick (Bristol and Prescott, 1968).

The formations at Cabot (Injection Zone—Franconia, Potosi, Eminence and Oneota formations and the Confining Zone--Shakopee Formation) present in the injection system are situated on the east flank of a small very gently plunging, dipping, anticlinal structure, which is located immediately west of the large LaSalle Anticline. This small anticlinal feature is the northern extension of an unnamed northwest trending anticline which can be referred to as the Bourbon Anticline. This structure has been extensively explored for oil from the Mississippian's Rosiclare at the Bourbon Consolidated Oil Field about 2 miles SW of the Cabot site. A few oil wells have also been drilled to the Rosiclare on a small domal structure about 1/2 mile NE of the Cabot site.

The detailed structure contour map shown in Figure 2-26 was constructed using the subsurface information for these oil wells and the deep injection wells of the area. This structure map a is detailed part of the larger map shown in Figure 2-14. The larger map includes the structure of the Rosiclare, in an area 2 1/2 miles in diameter around the site, as well as the structural contours on top of the Galena to the NE of the site (Haye's Pool). The two sets of structural contours seem to join in a smooth manner even though the surfaces mapped are nearly 2,000 feet apart vertically.

The Cabot wells are located on the east flank of a NS-trending anticlinal feature in the Rosiclare. This structure can also be seen on the structural contour map on top of the Hunton Megagroup (Bristol and Prescott, 1968), included as Figure 2-27.

Figure 2-28 is an interpreted structure contour map on top of the Galena using controls from the deep wells around the Cabot site. The top of the Galena was selected because it can be determined from drill cuttings or openhole logs with a great deal of accuracy. The contours on the Galena duplicate almost exactly the shallower structure in the Rosiclare. Since the formational units below the Galena are essentially parallel, or vary very gradually and systematically in thickness from SE to NW, expectations are that the shallower structure reflects from the deeper formations (Shakopee, Oneota, Eminence, Potosi). Figure 2-29 is a structure contour map of the top of the injection zone using the same deep well control and generally reflects the shallow structure. Based on the formation tops of the Cabot Tuscola Injection Well stratigraphic thickness between the top and bottom of the sedimentary package in the area around the Cabot Tuscola site. Because only a small amount of structural relief (35 feet) is present in this area and is nearly the same as the maximum difference in thickness (45 feet), it is not possible to make inferences about detailed structural features in deep units with any degree of confidence (given the limited number of wells present). However, the constancy in thickness offers an aid to structural mapping of deeper units, by incorporating the widespread subsurface control of a shallower unit (Rosiclare) to evaluate and infer overall deeper seated structural features surrounding the area of the Cabot Tuscola site.

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The detailed structure contour map shown in Figure 2-26 was constructed using the subsurface information for these oil wells and the deep injection wells of the area. This structure map a is detailed part of the larger map shown in Figure 2-14. The larger map includes the structure of the Rosiclare, in an area 2 1/2 miles in diameter around the site, as well as the structural contours on top of the Galena to the NE of the site (Haye's Pool). The two sets of structural contours seem to join in a smooth manner even though the surfaces mapped are nearly 2,000 feet apart vertically.

The Cabot wells are located on the east flank of a NS-trending anticlinal feature in the Rosiclare. This structure can also be seen on the structural contour map on top of the Hunton Megagroup (Bristol and Prescott, 1968), included as Figure 2-27.

Figure 2-28 is an interpreted structure contour map on top of the Galena using controls from the deep wells around the Cabot site. The top of the Galena was selected because it can be determined from drill cuttings or openhole logs with a great deal of accuracy. The contours on the Galena duplicate almost exactly the shallower structure in the Rosiclare. Since the formational units below the Galena are essentially parallel, or vary very gradually and systematically in thickness from SE to NW, expectations are that the shallower structure reflects from the deeper formations (Shakopee, Oneota, Eminence, Potosi). Figure 2-29 is a structure contour map of the top of the injection zone using the same deep well control and generally reflects the shallow structure. Based on the formation tops of the Cabot Tuscola Injection Well

CABOT CORPORATION TUSCOLA ILLINOIS PLANT

2007 PETITION FOR RENEWAL OF EXEMPTION FROM THE LAND DISPOSAL RESTRICTIONS

VOLUME 2

SECTION 2.0—SITE GEOLOGY

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2.0 SITE GEOLOGY

This section contains an evaluation and review of the subsurface regional and local geology present at the Cabot Tuscola Plant site and directly focuses on the suitability of the injection and containment formations.

2.1 INTRODUCTION

The geologic suitability of a specific stratigraphic interval for injection and confinement of wastes is determined primarily by the following criteria:

- lateral extent, thickness, porosity, and permeability of the injection reservoir
- lateral extent, thickness, porosity, and permeability of the overlying containment interval aquicludes and confining zone
- hydrogeologic compatibility of the injected waste stream with formation materials and formation brines
- presence of faulting or fracturing of the injection reservoir, overlying aquicludes, or confining zone
- seismic risk considerations.

These criteria are evaluated on the basis of the regional and local depositional and structural framework of the geologic section present under the Cabot Tuscola plant.

The geology and hydrology, as presented in this 2007 Petition for Renewal of Exemption from the Land Disposal Restrictions request, is derived from an integration of the original 1990 *Final Report on Supplemental Characterization for Cabot Tuscola WDW-1 & 2 No Migration Petition Demonstration* as prepared by Albert S. Nieto, Consultant and the *Final Petition for Exemption to Continue Injection of Banned Hazardous Waste*, previously prepared by Cabot's consultant, Texas World Operations, Inc. These documents were originally submitted in June 1990, to the U.S. Environmental Protection Agency (EPA), Region V, Chicago, Illinois, with additional data provided in July and August 1990. These documents were reviewed by EPA staff, and a determination was made that continued injection of wastes at the Cabot Tuscola facility met the No-Migration criteria set forth under the 40 Code of Federal Regulations (CFR) Part 148, 53 Federal Register 28117 (July 26, 1988). Where new information is available, it has been incorporated into this section, with a discussion of its potential impact on the original determination detailed.

This section contains a general discussion of the accepted and current knowledge about the evolution of the Illinois Basin, the general stratigraphy of the region of interest - east-central Illinois, and the setting of this region within the structural framework of the Illinois Basin. The regional area of interest, for purposes of this Petition Reissuance request, is defined as an area 45 miles in radius centered on the Cabot facility and its injection system. This area of interest was selected originally in the 1990 Cabot Petition, as part of a geological report characterizing the Tuscola area, prepared by Dr. Albert S. Nieto, Consultant, and Cabot has maintained and utilized these geological results for the current Petition Reissuance and Renewal document.

The Cabot Tuscola site is underlain by gently dipping, unfaulted and continuous sedimentary rock units. General geological knowledge and site-specific information, downhole geophysical logging, drill cuttings examination, x-ray diffraction of shale samples, completion and recompletion well data, etc., all demonstrate that the sedimentary rock units, at the level of the injection formations, members, and individual beds in this region of interest are laterally continuous. The sedimentary interval of interest is defined as the section from the bottom of the lowermost Underground Source of Drinking Water (USDW) (Silurian Moccasin Springs) to the base of the Injection Zone (Potosi, Franconia Dolomites). The injection system is favorably located on the east flank of a small anticlinal structure which limits any less dense fluids (lighter than the native formation brines) to migrate northwesterly in the opposite direction to the Tuscola Anticline. Additionally, included within this section are discussions of in-situ stresses and the regional and local seismicity of the area.

2.2 REGIONAL GEOLOGY

2.2.1 Evolution of the Illinois Basin

A review of current literature on the tectonics of the Illinois Basin and results from conferences with basin-analysis experts at the Illinois State Geological Survey (ISGS) indicate that deposition of sediments during the Late Cambrian and Early Ordovician times was essentially continuous. The injection interval rock units in this petition demonstration (Franconia, Potosi, Eminence, and Oneota Formations) were deposited during those times. Area information sources also indicate that deformation of the Illinois Basin occurred in Late Pennsylvanian times. This observation allows the delineation of documented structures disclosed by shallow-well control, to infer deeper structural features in the Injection Zone. These structural features provide and influence direct control over the long-term injectate migration and plume direction.

From the literature, it is generally recognized that the Illinois Basin began as a failed rift which formed near the end of Precambrian period in response to the breakup of a super-continent. High rates of subsidence in the resulting basin led to deposition of thick Early to Middle Cambrian sediments (see Figure 2-1 for a summary of the stratigraphic section penetrated by the Cabot Injection Wells). Compression associated with continental collision or associated with a simple increase of aesthenospheric drag at the base of the continental crust (as recently proposed by Nieto, 1990) in the Late Paleozoic and Early Cretaceous reactivated deformation of faulted and folded structures. The subsequent structures developed during this event represent the first major deformational episode of the Illinois Basin. Any faults which may possibly have existed at the rift margins were inactive from Late Paleozoic time. Since the Late Paleozoic deformation affects all the pre-Pennsylvanian formations, the shallow well control can infer deeper structural features in the Injection Zone. These structural features provide and influence direct control over the long-term injectate migration and plume direction.

Throughout most of the Paleozoic Era, the ancestral Illinois Basin was open to the sea (Iapetus Ocean) southwest of Indiana and Illinois. This period is characterized by small rates of subsidence (whether thermally induced by crustal cooling or mechanically induced by the aforementioned aesthenospheric drag), slow sedimentary deposition, and by lack of tectonic activity (Collinson et al., 1988). The sediments deposited during that time are called the Sauk Sequence (see Figure 2-12) and were the product of a major marine transgression with only minor emergent areas at basinal margins (Collinson, et al., 1988). The Sauk Sequence in the region of interest - east-central Illinois - is approximately 4,500 feet thick and comprises the Potsdam Megagroup, approximately 3,000 feet of mostly sandstones, siltstones and shales of Cambrian age, and the Knox Megagroup, about 1,500 feet of mostly carbonates of Cambro/Ordovician age. The Cabot Injection Zone is situated approximately within the middle of the Knox Group, the Eminence, Potosi, and top of Franconia Formations (see Figure 2-1).

The first major unconformity in this region occurs at the top of the Knox Group, approximately 1,000 feet above the top of the Cabot Injection Interval. It represents the sub-Tippecanoe erosional surface on which the St. Peter Sandstone was deposited. Sedimentation of carbonates continued to predominate in a gently subsiding basin throughout the Middle Mississippian time, however, terrigenous sediments (shales, siltstones and sandstones) predominate in the younger aged rocks. At least one thick shale sequence (the Maquoketa) was deposited in Ordovician times.

The Mississippian and Pennsylvanian periods are bounded by large unconformities. The unconformity at the top of the Pennsylvanian represents more than 125 million years and is marked by the absence of the youngest Pennsylvanian, virtually all of the Permian section, and all of the Mesozoic rocks older than Late Cretaceous.

2.2.2 Regional Stratigraphy

CAMBRIAN SYSTEM

The sedimentary sequence of the Injection Interval at the Cabot Tuscola site is part of a marine sequence of Cambrian and Ordovician age deposited near the basinal axis of the ancestral Illinois Basin. There are no apparent significant lateral changes in formation thickness or physical properties of the rock units of the Injection Interval (which lies within the uppermost Cambrian) for distances on the order of several miles.

Cambrian rocks which underlie all of Illinois are assigned an early Late Cambrian age and include the Mt. Simon, Eau Claire, Ironton/Galesville, Franconia, Potosi, and Eminence Formations. The Cambrian rocks in Illinois consist predominantly of sandstones and rest unconformably on top of Precambrian igneous rocks. As mentioned above, the predominantly sandy units are included as part of the Knox Dolomite Megagroup. In this region, the thickness of the Cambrian is approximately 3,300 feet (Figure 2-2). The Cambrian sequence and the Cabot Injection Interval located at the top of the Cambrian is considered to have good potential for disposal (Bergstrom, 1968; Visocky et al., 1986; Brower et al., 1989). The following individual stratigraphic descriptions have been generalized from standard references from the Illinois State Geological Survey (Buschbach, 1964; Willman, 1975; etc.).

Mt. Simon Formation

The Mt. Simon Formation composes the basal Cambrian unit, but was not penetrated by the Cabot Injection Well Nos. 1, 2, and 3. In east-central Illinois, it consists mostly of a fine-to-coarse-grained quartzose sandstone, partially conglomeratic with varied amounts of silica cement and average thickness of approximately 1,800 feet. Beds of variegated micaceous shale, up to 15 feet thick, are interspersed and occur in the uppermost 300 feet and lowermost 300 feet of the formation. The base of the Mt. Simon is the sub-Sauk unconformity, while the contact with the overlying Eau Claire Formation is conformable.

Eau Claire Formation

In northwestern Illinois, the upper two-thirds of the Eau Claire Formation consists of shales, dolomites, shaly dolomitic sandstones, and siltstones that show rapid facies changes gradationally from one to another. However, in east-central Illinois, the Eau Claire Formation consists of predominant shale (600 feet - 800 feet), while in southern Illinois generally it is dolomite and limestone.

This progression of rock-type from north to south indicates deepening of the ancestral water depths to the south from shallow, near-shore conditions to deeper marine facies near the depositional center of the ancestral Illinois Basin. This sedimentation pattern is observed throughout the Cambrian sequence. The Eau Claire Formation was not penetrated by the Cabot Injection Well Nos. 1, 2 and 3.

Ironton/Galesville Formations

The Galesville Formation consists of a few minor sandstones to 100 feet of fine-grained, moderately well-sorted, friable, non-dolomitic sandstone, while the Ironton Formation is composed of approximately similar thickness of coarse-grained, somewhat dolomitic sandstone. The Ironton/Galesville Formations overlie conformably the Eau Claire Formation in the northwestern half of Illinois, but are absent to the south because of gradational changes to dolomite. These formations are approximately 75 feet in the area, but were not penetrated by the Cabot Injection Well Nos. 1, 2, and 3.

Franconia Formation

The Franconia Formation (see Figure 2-1), which underlies all of Illinois, contains interbedded sandstone, shale, and dolomite, and ranges from less than 50 feet in northeastern Illinois to more than 500-700 feet in the southern portion of the state. In the region, the Franconia Formation is approximately 275 feet thick, while the basal unit is a shaly sandstone called the Davis Member. The Davis Member in east-central Illinois contains shale at the base and a silty to sandy dolomite in its upper portions. The Franconia was penetrated at a depth of 5,264 feet in Cabot Injection Well No. 1 (as determined by ISGS). Correlation with other deep wells which penetrated the section in the region suggest that the Franconia Formation may not have been penetrated in Cabot Injection Well No. 1. The top of the Franconia formation is probably within a few tens of feet from the total depth of the Cabot Injection Well No. 2. Approximately 27 feet of the Franconia may have been penetrated in Well No. 3 based on correlation with Well No. 1.

However, no distinct change in lithology from the overlying Potosi Formation was noted from the drill cuttings.

Potosi Formation

This formation is the lowermost unit of the Knox Megagroup as defined in this petition demonstration. The Potosi Formation lies conformably over the Franconia Formation and varies in thickness from 100 feet in northern Illinois to more than 300 feet in the southern portion of the state. It underlies virtually all of Illinois except for the northern portion where it has been truncated by the sub-Tippecanoe unconformity, where it lies directly under the St. Peter Sandstone. The distance from the Cabot Tuscola site to the nearest location where the Potosi Formation is in contact with the St. Peter Sandstone Aquifer is approximately 100 miles (see Figure 2-3). This constitutes the shortest direct path of discharge from the Potosi into the St. Peter Sandstone Aquifer.

The Potosi Dolomite in the area consists of a relatively pure, finely crystalline dolomite with fine-grained glauconitic dolomite present at the top, and sandy glauconitic dolomite at the base. The Potosi Formation contains interbeds of very fine to fine sandstone and argillaceous dolomite throughout its thickness. In east-central Illinois, the Potosi Formation contains thin layers of sandy shale with characteristics that include small cavities lined with drusy quartz, and small prisms easily recognizable in samples.

Eminence Formation

The Eminence Formation lies conformably over the Potosi and varies in thickness from 50 feet in northern Illinois to more than 250 feet in southern Illinois. The Eminence underlies most of Illinois except for the northern portions where it was eroded again during pre-St. Peter times. Figure 2-3 indicates that the thickness of the Eminence is approximately 180 feet around the Cabot Tuscola site with an increase to the southeast. It can be inferred (from Figures 2-2 through 2-4) that, during Cambrian and Ordovician times in general and Potosi/Eminence times in particular, the axis of the ancestral Illinois Basin was present immediately to the east of the site or near the Indiana-Illinois state line. The depositional center was located in SE Illinois and SW Indiana. Therefore, the Knox sediments in general and the Potosi/Eminence sediments in particular were deposited in deeper waters at the Tuscola site than those deposited to the northwest, in areas such as Manlove Field.

Evidence for lateral continuity of shale interbeds in the Knox Megagroup is demonstrated in the Local Geology section.

The Eminence Formation consists of light gray to brown or pink, sandy, fine- to medium-grained dolomite with oolitic chert and thin beds of sandy shale and fine to very fine-grained sandstone. The 1990 Nieto study examined sample drill cuttings of the Knox Megagroup from the two Cabot wells (Injection Well No. 1 and Well No. 2) and the Buck No. 2 well (Sect. 31, T16N, R8E, Douglas Co.). In general, the Potosi contained purer dolomite than the Eminence, and the sample study revealed that relatively thin layers of silty shale and fine-grained sand do occur in the Potosi/Eminence sequence in the area. The interbeds tended to be shalier in the Potosi and sandier in the Eminence Formation. No evidence of tidal lags, paleo soils (weathering, karstification), or any other evidence of unconformities within the Knox were observed or found. The Potosi and Eminence Formations represent the main section of the Cabot Injection Interval for this demonstration.

ORDOVICIAN SYSTEM

The Ordovician System underlies all of Illinois except for limited portions of its northern area where it has been eroded by the pre-St. Peter erosional event. The Ordovician System is predominantly composed of dolomites and limestones. This system ranges in thickness from 700 feet in the northern part of the Illinois area to more than 5,000 feet in the extreme southern part of this area. It is approximately 1,700 feet thick in the regional area. This system contains 26 individual formations of which 18 are carbonates, 4 are sandstones, and 4 are shales. Of these shales, the uppermost is the Maquoketa which is slightly over 200 feet in thickness. The Maquoketa represents a major hydraulic barrier to upward flow towards the lowermost USDW (Devonian/Silurian) of the region. However, layers of shale thinner than the Maquoketa but areally extensive on the scale of several miles also are present and exist even in the lowermost units of the Ordovician (Oneota).

Prairie du Chien Group

The Prairie du Chien group composes the lower part of the Ordovician rocks and consists of the Gunter Sandstone, the Oneota Dolomite, the New Richmond Sandstone, and the Shakopee Dolomite. In the southern half of Illinois, the Prairie du Chien becomes less sandy, more dolomitic and is grouped with the Knox Group. This gradation offers a conclusion and evidence of deeper waters to the south, however, the base of the Prairie du Chien cannot be picked with confidence where the basal Gunter Sandstone is not distinctive or is missing. From examination of cuttings from the Cabot and Buck wells, an increase in sand and green shale is observed in the lowermost 100 feet of the Prairie du Chien, with this interval in all probability containing the Gunter Formation.

Gunter Formation

The Gunter Formation is a thin unit that has been mapped continuously between LaSalle and McLean counties as a 10 to 25 foot medium to fine-grained quartzose sandstone, with quartz grains moderately well sorted and sub-rounded to sub-angular. The Gunter Formation also contains thin beds of fine-grained dolomite and small amounts of green shale (Buschbach, 1975). This unit is recognized in openhole geophysical logs and at the Manlove Field in Champaign County, as a 4-foot to 10-foot sandy, dolomitic shale or siltstone. The unit corresponds to the sandy/shaly interval easily recognized in the gamma-ray log of the Cabot, Buck No. 2 and USI wells located within the depth interval of 4,800-4,900 feet. (Separately, the Illinois State Geological Survey has picked the top of the Gunter Formation approximately 30 feet lower than this distinctive sandy/shaly layer thus, this unit is extensive throughout the area).

Oneota Formation

The Oneota Dolomite overlies the Gunter Formation and is overlain conformably by the

New Richmond Sandstone in the northwestern half of the state. However, in the region of interest, the New Richmond is not well defined, and the Oneota is overlain directly by the Shakopee Dolomite. The Oneota consists of fine- to coarse-grained, light to brownish gray, cherty dolomite and also contains a few friable sandstone and glauconitic sandy shale intercalations. The Gunter Formation can be considered the lowermost of these intercalations. The Oneota ranges in thickness from 100 feet in the north to slightly over 300 feet in the regional area. The Oneota represents the containment interval and immediate confining section for this demonstration.

Shakopee Dolomite

Pre-St. Peter Formation solution effects and erosional activity has removed extensive portions from the top of the Shakopee Dolomite in the northern part of the state. However, in east-central Illinois, the Shakopee Dolomite varies in thickness only slightly, thickening regularly to the southeast with observed variation in thickness approximately 100 feet in 50 miles. The virtual constancy of thickness of the relevant sedimentary sequence for this demonstration event (Mississippian to Cambrian), even in the presence of a major erosional event (Pre-Tippecanoe), will be discussed later in this demonstration as an aide to structural mapping.

Lithologically, the Shakopee Dolomite varies from argillaceous (clayey) to pure dolomite with thin interbeds of sandstone, shale, and siltstone. The Shakopee is designated the Confining Interval here, with interbeds of sandstone and shale being considered as very favorable characteristics for containment in this injection system. The shales act as direct barriers to flow, and the sands behave as pressure relief dissipaters. Although no specific hydraulic conductivity data is present, the sands due to their favorable reservoir properties can store large volumes of fluid and hold pressure as a relief reservoir.

Ancell Group

The next shallowest overlying rock group is the Tippecanoe Sequence which begins with the St.

Peter Sandstone and includes the rest of the Ordovician, all the Silurian, and the Lower Devonian. In the regional area, the Ordovician portion of the Tippecanoe is composed of the Ancell Group (St. Peter and Joachim Formations), the Platteville Group, and the Galena Group.

The St. Peter Sandstone was deposited on the erosional surface on top of the Shakopee Dolomite (top of Prairie du Chien) in the area. The thickness of the St. Peter Sandstone varies moderately (from 150 feet to 200 feet) in the region, due to minor relief on the Shakopee erosional surface (Illinois Chamber of Commerce Docket No. 46678, 1960, p. 29). The upper half of the St. Peter in the area is silty and is not as clean as in other areas of Illinois, since it is composed of medium to fine-grained, well rounded, frosted sandstone with traces of shale and limestone (see Appendix 2-2 for analysis of core plugs from the St. Peter).

The St. Peter is overlain in east-central Illinois by the Joachim Dolomite, which is the upper formation of the Ancell Group. The Joachim Dolomite underlies all of east-central Illinois, thickens southward regularly, and is lithologically highly varied containing individual persistent beds of argillaceous, silty, sandy dolomite, pure dolomite, sandstone, and limestone. Layers of anhydrite, mud tracks, and ripple marks suggest deposition in a shallow, closed basin. However, in spite of the shallow nature of the environment of deposition, the overall thickness of the Joachim varies only very slightly, with thickness variation in the area less than 100 feet in 50 miles (Willman, 1975).

Platteville and Galena Groups

The Platteville Group overlies the Ancell Group and underlies the Galena Group. It exhibits sharp upper and lower contacts that are interpreted as minor unconformities and underlies all of east-central Illinois. In the regional area, the Platteville Group is dominantly lithographic, mottled, dolomitic, slightly shaly limestone and contains widely traced beds of bentonite. These bentonite beds are effective multiple hydraulic barriers which isolate and contain the Cabot Injection Zone formations from the lowermost USDW.

The Galena Group consists of limestone and dolomite formations and is present in all of the state except in the central portion of northern Illinois and along the crest of the LaSalle Anticline, notably in LaSalle County, where the Galena was eroded prior to Pennsylvanian times. The Galena Group is 250 to 275 feet thick in the northern region and approximately 150 feet in the area, but unlike most of the sedimentary units of the Illinois Basin, the Galena thins southwardly.

Maquoketa Group

The Maquoketa Group caps the Ordovician System and rests on a regional unconformity over Galena rock and is overlain unconformably by the Silurian System. As indicated earlier, the Maquoketa Group represents a major hydraulic barrier isolating the Cabot Injection Zone formations from the lowermost USDW (Devonian/Silurian). Generally, the Maquoketa consists of a lower shale unit, the Scales Shale, a relatively thin limestone, the Fort Atkinson Limestone, and an upper shale, the Brainard Shale. The Maquoketa Group underlies essentially all of Illinois except for the northern portions. In Illinois the closest distance from the Cabot site to a location where this shale barrier has been eroded is observed approximately 100 miles to the northeast. In the area, the Maquoketa ranges in thickness from 200 feet to 250 feet and at the Cabot site, it is slightly over 200 feet thick.

SILURIAN AND DEVONIAN SYSTEMS

The Hunton Megagroup includes all the Silurian in the regional area of interest, as well as the overlying Devonian carbonates. The rocks consist of predominantly carbonates and become almost entirely dolomites in the northern part of the state. The thickness of the Silurian System is approximately 550 feet in the area.

Devonian strata in Illinois are subdivided into Lower, Middle, and Upper Devonian periods. A major unconformity separates the Middle and Upper from the Lower Devonian. In east-central Illinois, Lower Devonian rocks are absent, and Middle Devonian rocks overlie Silurian rocks. In the Middle Devonian, the carbonates are namely the Wapsipinicon Limestone and the overlying Cedar Valley Limestone.

The New Albany Shale Group, which is gradational from Upper Devonian to Basal

Mississippian, overlies the Hunton Megagroup. The Wapsipinicon Formation of the Hunton Megagroup in east-central Illinois is composed generally of fine-grained to lithographic, partially sandy limestone and dolomite. Overlying the Wapsipinicon, the Cedar Valley Limestone consists of dominantly crystalline to sublithographic grayish-brown limestone with shaly interbeds and occassional clean sandstone at the base. The New Albany is a series of black to brownish, carbonaceous, shale with minor amounts of dolomite and sandy dolomite. The Silurian and Devonian rocks represent the lowermost (deepest) USDW for the Cabot Tuscola site.

2.2.3 Formations Above the Lowermost USDW

The contact between the Devonian and Mississippian Systems is conformable nearly everywhere in Illinois and occurs within shales of the New Albany Group. Many structural features were formed or reactivated at the close of the Mississippian Era. Uplifted areas underwent subsequent erosion, and a major unconformity is found to separate the Mississippian and Pennsylvanian Systems. Only Lower Mississippian strata are present in the region consisting of a few tens of feet of dolomitic limestone (Kinderhookian) and approximately 500 feet of thick, argillaceous, slightly calcareous, glauconitic, fine-grained siltstone with lesser amounts of silty shale (Borden siltstone).

Pennsylvanian rocks form the bedrock surface ~~in~~for most of Illinois (Kolata, 2005). This surface has been eroded as a result of the Late Paleozoic deformation and further eroded during the Pleistocene glaciation. Pennsylvanian rocks characteristics include many vertical changes in lithology, some frequently abrupt, which can produce many laterally extensive sandstones, siltstones, coal-seams, underclays, and shales.

The balance of subsurface formation materials in the region are sediments of Quaternary age, ranging in thickness from less than 50 feet to more than 400 feet and consist of Pleistocene glacial drift and various types of Holocene soils.

Thickness Variation of Mississippian/Cambrian Sequence

Table 2-1 shows the depths (depths in Column 1) of the Rosiclare and the thickness of sedimentary rock between it and the top of the Shakopee, Oneota, and Eminence formations based on four deep-wells with modern well logs in a one-mile radius around the Cabot Tuscola site. This Mississippian/Cambrian sequence represents the containment, confinement, and secondary confinement interval for the Cabot Tuscola Petition Demonstration. The maximum difference in elevation is 35 feet of structural relief between formation tops of the Rosiclare Formation, with maximum variation in thickness of 45 feet between the Rosiclare and the Eminence. From Table 2-1, the maximum thickness variation observed between the wells is only 1.5% of the total thickness. This indicates that although several important unconformities exist within the sedimentary section, there remains remarkable consistency and conformity in the stratigraphic thickness between the top and bottom of the sedimentary package in the area around the Cabot Tuscola site. Because only a small amount of structural relief (35 feet) is present in this area and is nearly the same as the maximum difference in thickness (45 feet), it is not possible to make inferences about detailed structural features in deep units with any degree of confidence (given the limited number of wells present). However, the constancy in thickness offers an aid to structural mapping of deeper units, by incorporating the widespread subsurface control of a shallower unit (Rosiclare) to evaluate and infer overall deeper seated structural features surrounding the area of the Cabot Tuscola site.

Only very slight and regular variation in thickness at the area of the Cabot Tuscola site is present (see Figures 2-2, 2-4, 2-6, and 2-7) as indicated in isopach maps of the major geologic systems (Cambrian, Ordovician, Silurian, Devonian, and Mississippian) as well as of the Shakopee Formation (Figure 2-5).

2.2.4 Regional Structural Geology

Figure 2-8 consists of a map of the north-central United States showing the extent of the Illinois Basin and surrounding major structural features (Collinson et al., 1988). Figure 2-9 details the major structural features within the Illinois Basin. The structure on top of the Trenton (Galena) or equivalent in the Illinois, Michigan, and Forest City basins is presented in Figure 2-10. The structure on top of the Prairie du Chen Group is presented in Figure 2-11. The Illinois Basin is closed to the south by the Pascola Arch (not shown in the figure because it lies under the Mesozoic sediments of the Mississippi Embayment). The Pascola Arch is a major structural high between the Ozark Uplift and the Nashville Dome. The Pascola Arch is a relatively recent feature, because as indicated previously, stratigraphic evidence shows that the Illinois Basin was an open trough to the south during most of Paleozoic time. The time when the Pascola Arch developed is not certain but it is quite probably rather late in Paleozoic time. This represents the time that marks the beginning of the major tectonic activity responsible for all of the structural features within the basin. Figure 2-12 includes north-south and east-west cross-sections of the Illinois Basin (Collinson et al., 1988). The cross sections indicate that the folding and faulting that affects younger sediments also equally affects the oldest sediments, providing direct evidence of the relatively late age of the major deformation (Treworgy, et al 1990).

The main structural feature in the area is part of the LaSalle Anticlinal Belt (see Figure 2-9) which is locally known as the Tuscola Dome or Anticline. The axis of this strongly asymmetrical fold is located approximately 3.5 miles ENE of the Cabot Tuscola site and has an axial plane with a bearing of approximately N 20° W. The west flank of the LaSalle Anticline is steeper, with dip values being rather gentle, at approximately 6° immediately north of Tuscola and a dip of less than 10° along its northern extension, near the boundary between Champaign and Douglas Counties.

Localized steeper dips in excess of 30º are observed on the western limb away from the crest of the anticline. The range of widths of the western limb, as observed from subsurface control, varies between 5 and 10 miles, and relief for the LaSalle Anticlinal Belt varies between 1,500 and 3,000 feet. If the maximum dip of 30º is used to calculate the structural dip for the western limb, assuming 5 miles in width, a total relief of 15,000 feet is obtained instead of 3,000 feet.

Thus, steep dips observed are only very localized and, in all likelihood, are caused by the same mechanism responsible for the development of the LaSalle Anticlinal Belt. High dips do exist but, in all likelihood, are very local features and do not extend over large areal extent or indicate widespread fracturing.

Collinson et al. (1988) showed a fault with strike parallel to the axial plane of the LaSalle Anticline on the western flank, east of the Cabot Tuscola site. However, conferences held between Nieto for his report with Messrs. James Eidel, Mineral Resources and Engineering Branch Head, Dennis R. Kolata, Basin and Crustal Analysis Section Head, and Michael L. Sargent, Basin and Crustal Analysis Section, Illinois State Geological Survey, indicated that it was recognized that no evidence exists for such a fault other than geological interpretations.

2.2.5 Subsurface Structure Mapping

The lack of deep wells into the Cambrian/Ordovician Formations in the region offer extreme difficulty to construct any detailed structure map of these deep Injection Interval formations. A structure map is needed to determine the long-term path of the waste plume migration and identify concentrations of the injectate discounting and not considering hazardous constituents neutralization in this demonstration. The lighter injectate will migrate updip under the containment interval with velocities proportional to the dip of the beds, and a density difference between injectate and formational brine.

The general approach employed to structure mapping of deep formation units is based on the well control available in the shallow unit (Rosiclare). This approach is based on two considerations:

1) major deformation of the Illinois Basin took place in late Paleozoic times, hence, deformation will influence and affect shallow structures as well as deeper ones; and

2) in spite of major unconformities within the sedimentary sequence of interest (Mississippian/Cambrian), remarkable constancy exists in the section thickness penetrated by the few area deep wells around the Cabot Tuscola site (west of the LaSalle Anticline axis).

Therefore, the assumptions can be made that west of an area between the site and the anticlinal axis, all the units below the top of the Mississippian have not been affected by erosion and are continuous. This specific area between the Cabot Tuscola site and the anticlinal axis is specified because obviously, near the axis, pre-Pleistocene erosion has eliminated Mississippian and even older sedimentary units.

A detailed structure contour map on top of the Rosiclare Formation (see Figures 2-13 and 2-14), which is considered the top of the Mississippian, and two regional cross-sections (see Figures 2-15 and 2-16), should reflect (west of the anticlinal axis) not only the structure on top of the shallower Rosiclare Formation but also indicate structure in the deeper formations (Cambrian/Ordovician).

The use of relatively shallow structures to infer deeper structures, at least in east-central Illinois, is further substantiated by comparison of structure contour maps of the Galena and Prairie du Chien (Figures 2-10 and 2-11). The correlation of structural features in those two maps is apparent, with irregular contours of the Galena map simply reflecting a greater density of subsurface control points. Details of the local structure of the Injection Zone at the Cabot Tuscola site are discussed in the local geology section.

2.2.6 In-Situ Stresses

The in-situ state of stress present in a rock mass is an important factor that controls:

a) the potential onset of hydraulic fracturing by injection operations,

b) the potential enhancement of vertical and horizontal permeability of the rock mass (by a change in the normal stresses acting across existing rock mass discontinuities), and

c) the seismic activity of the region.

A preliminary approach to evaluation of in-situ stresses in (younger) sedimentary-rock environments is to assume that in-situ stress is controlled exclusively by gravity loading. Under these conditions, if the rock is assumed to behave elastically, the magnitude of the in-situ stresses can be estimated by elastic theory (e.g. Goodman, 1989):

$$\sigma_v = [\gamma]z$$

and

$$\sigma_h = \sigma_v \frac{\mu}{1-\mu}$$

where

σ_v = vertical stress

σ_h = horizontal stress

γ = unit weight of ground materials

z = depth below the ground surface

μ = Poisson's ratio

Typical values of Poisson's ratio range from 0.25 to 0.33; therefore, in young sedimentary-rock environments with the magnitude of the horizontal stresses at any depth, ranges from 0.33 to 0.5 times the vertical stress. However, this initial stress field becomes more complex as the in-situ stresses are affected by several geological processes such as tectonic movements, erosion, glaciation, etc. The net effect of these processes in some regions is to increase the value of the horizontal stresses. Extensive in-situ stress measurements (Zobak and Zobak, 1981; Hoek and Brown, 1980; Haimson, 1988; Nelson and Bauer, 1987) indicate that in the central U.S. vertical stresses are in fair agreement with the simple predictions given above (overlying weight of rock), but that the horizontal stresses are usually in excess of the value predicted by elastic theory. Figure 2-17 shows areas in the central U.S., where the magnitude of the stress ratio of average horizontal-stress-to-vertical stress, Ks, near the surface can be as high as 3 or 4 and that it decreases with depth to values slightly under 1.0, in a hyperbolic manner. In-situ stress measurements both in southern and northern Illinois, at depths of less than 3,000 feet, yield horizontal stresses which are at least equal to vertical stresses (Nelson and Bauer, 1987; Shuri and Kelsay, 1984). The fact that horizontal stresses, particularly at shallower depths, are actually larger than predicted by elastic theory and gravity loading, has important implications in the closing of any vertical fractures and thus in reducing the potential for upward fluid migration. Figure 2-18 is a map of the United States with the orientation of principal horizontal stresses. One sees that in Illinois, the orientation of major principal stress is ENE-WSW, which is normal to the axis of the LaSalle Anticlinal Belt. Since little observed or recorded operational pressures have been induced as a result of the Cabot Tuscola injection well operations, it is logical to assume that neither hydraulic fracturing nor injection-induced seismicity are remotely possible at the Cabot Tuscola site.

2.2.6.1 Jointing and Fractures

Joints and other systematic fractures in Illinois can be of two types:

1) joint systems associated with the contemporary state of stress of the region and,

2) joints and systematic fractures associated with the faulted structures.

Both types of fractures are known to have very steep-to-subvertical dips (e.g. Foote, 1982). Recent studies conducted at the Geology Department of the University of Illinois (Foote, 1982), Illinois State Geological Survey (Nelson and Bauer, 1987), and elsewhere (Engelder, 1982) indicate that within Illinois and surrounding states, the best developed joint direction coincides with the present-day orientation of the maximum in-situ compressive stress (ENE, WSW). The orientation of the maximum in-situ compressive stress is, as previously mentioned, also normal to the axial plane of the LaSalle Anticline. These observations lead to the remarkable conclusion that jointing and folding of the Illinois Basin are probably connected to present-day stress fields. A corollary of this conclusion is that the orientation of the compressive fold that created joints and folds in late Paleozoic times (the LaSalle Anticline was most probably developed mostly in post-Mississippian times) has remained essentially unchanged (additional discussion on the origin of the LaSalle Anticline, faulting, and present-day stresses is in the next section). Jointing in units such as the Oneota/Eminence/Potosi occurred while these units had at least the same amount of formation overburden as they do today. These joints (if present) at the Cabot Tuscola

Injection Zone, have never had the opportunity to release and/or separate as joints might, if brought close to, or on the surface by erosion. All indications are that high horizontal compressive stresses exist in the midcontinental region, therefore, these stresses should maintain vertical joints and fractures quite closed and tight at the depths of the Oneota (Cabot immediate Containment Interval) and the Eminence/Potosi Formations (Cabot Injection Interval). Furthermore, field studies (e.g. Price, 1966; Nieto, 1977) of vertical joints show that they develop preferentially in brittle rocks with high elastic modulii such as dolomites, and that their development is arrested in plastic, deformable rocks such as shales; the latter type develops micro-fractures rather than systematic jointing. Thus, the shales in the sedimentary sequence discussed here will interrupt any tight vertical joints that may exist in the carbonate and sandstone layers.

Commonly, sets of systematic joints associated with large faults exist, and normally these sets have attitudes that parallel the attitudes of such large-displacement fractures. However, since there is no evidence of faulting in the area, the conclusion is that systematic joints associated with significant faults should not be present, based on the non-brittle behavior of the sediments. The localized compressive stresses in the center of the Illinois basin have acted as long as the basin has subsided actively (i.e., hundreds of millions of years). Time dependent rheologic properties are required to explain deformation, and creep deformation of rock is also a well documented phenomenon (e.g. Hardy etal, 1970; Rutter, 1972; Afrouz and Harvey, 1974; John, 1974; Jaeger, 1976; Goodman, 1989; Cristescu, 1989).

Non-systematic fracturing probably exists in the dolomite layers of the site, and if so, fracturing of this type does have a large influence on the homogeneity of formation layer permeability. Almost all dolomite (dolostone) is secondary in origin and forms as the result of a mineralogical transformation of calcite (limestone) (e.g. Pettijohn, 1957; Freeze and Cherry, 1979). Because the crystalline structure of dolomite occupies approximately 13% less volume, the process of dolomitization is accompanied by a development of vugs, microfractures, enlarged pores, and a resultant increase in secondary porosity and permeability. With time these secondary voids may become lined and sometimes are filled with secondary quartz and carbonate crystals (druses, veins, and geodes). Both the Eminence and Potosi dolomites exhibit and document vugs and druses. Although some void filling has probably taken place in these formations, their permeability is still controlled by secondary fractures and voids. High permeability of the injection interval cannot be ascribed to primary porosity or tight systematic fractures or joints. The only fractures or openings that could remain open in a high compressive stress field are ones with small dimensions perpendicular to the compressive stress direction, i.e. small non-systematic fractures. These non-systematic fractures and voids developed in the very distant geologic past during dolomitization and are not related to jointing and systematic fracturing discussed earlier.

Spacing and dimensions of these diverse types of fractures can vary by orders of magnitude, with joints and systematic fractures exhibiting spacings and dimensions usually between several inches (near faults) to several tens of feet. The non-systematic fractures and voids associated with dolomitization have dimensions and spacings that vary from microscopic to a few inches. Careful testing of large cores (of at least 6 inches in diameter) can give good approximations of the permeability controlled by vugs and microfractures (non-systematic fractures). Permeability measurements on small, 1-inch core plugs invariably underestimate the permeability of vuggy and micro-fractured dolomite because those specimens only indicate matrix permeability. Permeability affected by vugs and microfractures is usually not tested in the laboratory since the dimensions of the plugs are of the same order of magnitude as the vugs and invariably can fracture during sample preparation. Permeability controlled by joints and systematic fractures can only be measured by means of in-situ tests. All lab permeabilities reported for Cabot Tuscola Injection Well Nos. 1, 2, and 3 were obtained from core plugs less than 1 inch in diameter. Thus, higher permeability values are exhibited in the field (as evidenced by initial lost circulation experience during drilling of the Cabot injection wells and other deep wells in the area). These high permeability values were utilized as justification and validation input assumptions for the reservoir model layers used in flow and containment modeling.

2.2.6.2 Origin of Folding, Faulting and Jointing

Faulting and jointing that could be associated with the development of the nearby LaSalle Anticline is discussed here. A review of deformational features of the Illinois Basin and regional structural geology shows no evidence for faulting near the LaSalle Anticline exists nor should be expected. The state of stress responsible for the development of the anticline and the main joint system of the Illinois Basin is the same as that which exists today. Furthermore, the joints that may exist in the Cabot Tuscola Injection Zone formations have not had an opportunity to become decompressed due to injected fluid since high permeability is present in the formation matrix, and insufficient pressure buildup has been present to activate the jointing in the formations.

The Illinois Basin, like other intra-cratonic sag basins such as the Michigan and the Willingston Basins, have remarkably similar anticlinal belts in their midst. The Howell Anticline in the Michigan Basin and the LaSalle Anticlinal Belt have been thoroughly studied and compared (Fisher et al., 1988; Heinze and Braile, 1988). In both cases these folds present are associated with the measured present-day in-situ stress field(s). These anticlinal belts are not faulted and can be explained as a result of long-acting compressional stresses developed in the middle of the sag basins as the crust subsided to create the basin. This high compressional field in the middle of a subsiding surface is well documented in mine-subsidence engineering (see Figure 2-19 for theoretical and observed compressive strains in the middle of a subsidence bowl). The crust acts as a plate which develops a local depression, and the upper fibers (above the neutral axis) of such surface deformed plate will develop compressive strain with the highest values centered at the depression (e.g. Gere and Timoshenko, 1984). The compressive field decreases toward the margins of the depression and eventually becomes tensile. If the plate was preloaded horizontally before deformation, the margins only experience a reduction of the compressive preload (extension) near the edges of the depression. Any materials lying on top of such plate (such as a sedimentary fill) will be deformed accordingly.

Recent seismic activity (Hamburger and Rupp, 1988), recent surface deformation (Rims, 1982), and roof rock falls in coal mines (Nelson and Bauer, 1987) have been linked directly to the present in-situ stress field. Buckling of quarry floors in northern Illinois and well documented movement of valley walls (inward toward the valley axis) (Nieto, 1977) are further evidence of the presence of a contemporary, high horizontal-compressive stress field. Finally, as discussed in the previous section, systematic jointing is also associated to the present in-situ stress field. One must conclude, therefore, that the structural features at least in the east-central part of the Illinois Basin, whether folds or joints, are intimately associated with an ENE-WSW-trending compressional stress field. The faults in the southern part of the state, Rough Creek, Cottage Grove, St. Genevieve, Pennyrile, etc., are associated with the development of a more recent sag - the Mississippi Embayment and not related to the Illinois Basin (Nieto, 1990; Cremeens, 1990).

A remaining issue related to the LaSalle Anticline is the possible presence of undetected faults. Large plastic deformation of rock does not necessarily require high all around stress (σ_3) or associated fracturing. It can occur simply under long-acting, relatively small differential stresses (Cristescu, 1989). In fact, rheological studies in rock indicate that creep (time-dependent deformation under constant differential stresses) is a general phenomenon in all rocks and can take place at any stress level. Near surface materials (both soils and rocks) adjacent to slopes, for instance, evidence large amounts of deformation caused by creep. Photographic examples of deformed rocks associated with slope creep can be found in Kirby, 1982. Therefore, the development of a gentle fold such as the LaSalle Anticline can easily occur without any associated faulting.

In summary, there is firm evidence that the stresses that developed the LaSalle Anticline have been active since late Paleozoic times and that, therefore, there has been no appreciable variation in the stress field since those times. High horizontal stress values, responsible for the development of the LaSalle Anticline, still exist today and should be effective in tightening any systematic jointing (but not faulting) that may exist in the area of the Cabot site.

Field work indicates that well developed joint systems at the surface are not generally observable in coal mines at depths of several hundred feet in central southern Illinois (Nieto and Donath, 1976; Nieto-Pescetto et al., 1973). The high horizontal stress field is a very effective means of tightening up any type of systematic jointing.

Still the issue could be raised that the high permeabilities that are experienced at the Cabot Tuscola site could be interpreted as being vuggy or fracture controlled, however this does not match reservoir falloff data. Another possible interpretation is that lost circulation commonly occurs in the Eminence/Potosi throughout the Illinois Basin, irrespective of nearby folds due to underpressure conditions. The vuggy and microfractured nature of these formations and the presence of numerous sandy interbeds throughout them can account for these high permeabilities. Therefore, it is not likely that fault-associated systematic fracturing at the Cabot Tuscola site is present, simply because high permeabilities are the typical background in these formations due to major matrix enhancement from hydrocholoric acid waste with the dolomite grains and free calcite available.

No faulting or "open" fractures are expected or associated with the site because of the close proximity to the LaSalle Anticline. The high horizontal permeabilities found in the Cabot Tuscola Injection Zone are reflective of sedimentary features enhanced by orders of magnitude with dissolution of grain boundary cement by the Cabot acid waste stream, and not structurally controlled attributes of these formations.

2.2.7 Seismicity

Earthquakes are relatively infrequent events in east-central Illinois, since most of the earthquakes recorded have low to moderate intensities and magnitudes. The frequency and intensity of earthquakes increases toward southern Illinois, with the largest earthquake recorded occurring in the New Madrid, Missouri area during 1811-1812. On the Modified Mercalli Intensity Scale, estimates are that the New Madrid earthquake generated an intensity of at least IX in the Ohio Valley area of Illinois. On the Richter Scale, it is estimated that this earthquake registered a magnitude of 7.2. The Richter Scale is a relation of the ground movement to the amount of energy released. Since this scale is logarithmic, an increase in one whole number represents a tenfold increase in energy released (Brower and Visocky et. al., 1989).

Brower and Visocky et. al. (1989) reported that the largest earthquake registered this century for Illinois occurred in 1968, with this earthquake showing a magnitude of 5.5 and maximum intensity of VII near the epicenter in southern Illinois (Hamilton County). A more recent earthquake occurred in 1972, and was investigated in detail by Heigold (1972). On the Richter Scale, the 1972 earthquake registered a magnitude of 4.6. The epicenter was located at the northern end of the Illinois Basin in southern Lee County. It is believed that a zone of weakness was present, and the epicenter was located where the La Salle Anticline merges with Ashton Arch.

Earthquakes originating in east-central Illinois are relatively infrequent and nondestructive. Records dating back to 1804, indicate that no earthquakes with intensities greater than VIII on the Modified Mercali Scale have occurred in the region (Heigold, 1972). Figure 2-20 shows locations of epicenters and intensities of earthquakes that have occurred in Illinois. Several fault systems have produced complex areas which may be subject to infrequent seismic activity. These areas have been identified as the Wabash Valley Fault System and the St. Genevieve-Cottage Grove-Shawneetown Fault Zones.

Figure 2-21 shows locations, event magnitudes, and dates of occurrence for epicenters within a 50 mile radius around the Cabot site, through July 1998. A recorded event in February 1978, occurred approximately 3-1/2 miles east of the Cabot site. Another low intensity event in April 1990, has been located at variable calculated offset positions from 7 miles southwest, 16 miles south-southeast, or 44 miles southeast of the Cabot site. The Saint Louis, Missouri seismic station is the main source that located the epicenter of this event and recorded it at a distance of 44 miles from Cabot. A list of these recorded seismicity events is found in Appendix 2-1. Many of the seismic events listed are duplicate reports, some with differing locations for the event epicenter due to multiple recording stations and event resolution. Several other seismic events occurred within a 50 mile radius prior to the initiation of injection by Cabot (1966). There has been no increase in seismic activity since the start of injection.

The United States Geological Survey National Earthquake Information Center online database was searched in January 2007, for any new information since preparation of the permit renewal applications. No new earthquakes have occurred within 100 kilometers of the Cabot facility since the last reported earthquake in 1996, which was located approximately 83 kilometers from the site. Copies of the updated earthquake database searches are included in Appendix 2-1.

Nelson and Lumm (1984) cite numerous studies, primarily from southern Illinois, which indicate that the modem stress field is one of compression, with the principle stress axis oriented in an east-west to northeast-southwest direction. Where strain gauge measurements were taken, maximum lateral recorded compressive force was more than three times the vertical loading.

These lateral stresses are apparently creating thrust faults in near surface strata and producing earthquakes through reverse and strike-slip offset in deeper rocks.

As previously noted, there has been no observed increase in earthquake activity near the Cabot site since injection began. There is no danger of injection induced earthquakes since the pressure required to induce fracturing in the injection interval has been calculated to be in excess of 800 pounds per square inch (psi), and the maximum permitted allowable surface pressure for the Cabot facility is limited to 50 psi.

A seismic risk map, Figure 2-22, divides the state into three areas of expected damage from an earthquake. Region three in southern Illinois has the greatest risk for severe damage from an earthquake. The risk in this region is attributed to the higher frequency of occurrence of earthquakes associated with the New Madrid fault and seismic area. However, earthquakes of magnitudes greater than 5.7 are very infrequent and, north of this area, the risk of severe damage decreases since the area becomes less seismically active with distance.

2.3 LOCAL GEOLOGY

The discussion of the local geology has been adapted from Cabot's previous geology submittal, and the associated Nieto report. Both of these documents were prepared prior to the drilling and completion of Injection Well No. 3 at the Cabot site and did not incorporate key findings from that well, however, Cabot has included all known information from Injection Well No. 3 in this report.

Additional site specific geological and hydrological data was obtained during the drilling of Cabot's Injection Well No. 3 and was compared with the data used in the original petition demonstration. Formation structural tops, thicknesses, and lithology descriptions obtained from information recovered in Injection Well No. 3 are shown to provide little variation from the earlier data and values recorded from Well No. 1 and Well No. 2. Petrophysical parameters used in the original Cabot reservoir modeling were demonstrated to be conservative relative to the site specific data determined from recovered cores during the construction of Well No. 3.

2.3.1 Local Structural Geology

The Cabot injection wells are located approximately 3 miles west of the town of Tuscola. Topographically, the region is relatively flat with a local relief of less than 50 feet, and surface elevations ranging from 600 feet above sea level in the south near the Embarras River to over 760 feet north on Yankee Ridge.

Structurally, the Tuscola area lies at the northeastern edge of the Fairfield Basin in the center of the La Salle Anticlinal Belt (see Figure 2-9). The anticlinal belt includes the Tuscola Anticline, Murdock Syncline, the Northern end of the Cook Mills Anticline, and the northwest corner of the Brocton Dome. Figure 2-23 is a schematic structural cross-section from the Cabot site to the crest of the Tuscola Anticline showing local dip to the west, off of the Tuscola Anticline. The cross-section depicts the continuity of the Cabot Injection Zone and Confining Zone, and demonstrates the thickness of Devonian, Mississippian, and Pennsylvanian aged sediments which are absent from (caused by erosion or non-deposition) the crest of the anticline.

During the Lower and Middle Paleozoic Era, the Tuscola area was part of a large shallow basin that underwent rather uniform shallow marine deposition. Cambrian deposition consisted of sandstones and dolomites with few shale occurrences, the exception being the Eau Claire Formation, which contains thin shale sequences. Lower and Middle Ordovician deposition was similar to Cambrian, except fewer sandstones were deposited. During Upper Ordovician, the Maquoketa, a thick shale sequence, was deposited over the 4,000 to 5,000 feet of previously deposited carbonates and sands. Maquoketa Shale thicknesses in the area range from 180 to 230 feet (Bristol and Prescott, 1968).

As previously stated, uplift of the La Salle Anticlinal Belt, which includes the Tuscola Anticline, began near the end of the Mississippian and continued at least through the end of the Pennsylvanian (Nelson, 1995). Figure 2-24 shows the Pre-Pleistocene bedrock surface in the Tuscola area. Silurian age units are the oldest formations exposed on the crest of the anticline. The cross sections included in Figure 2-24 agree well with Figure 2-23. The geological formations of the Cabot Injection Zone and Confining Zone are intact, and not breached across the crest of the Tuscola Anticline and the mapped area.

During the formation of the anticlinal structure, a simultaneous downwarp of the Fairfield Basin was occurring. Pennsylvanian sediments were rapidly filling the basin and, by the end of the Pennsylvanian, sediments had completely filled the basin. Uplift probably continued after Pennsylvanian time, evidenced by the Kewanee and McLeansboro Groups, which are found dipping away from the crest on both sides of the anticline (Bristol and Prescott, 1968). As discussed earlier, more than 2,500 feet of Pennsylvanian, Mississippian, and Devonian Rocks are absent from the crest of the anticline, and it is difficult to determine when anticlinal growth had terminated.

Figure 2-25 shows the distribution of the bedrock surface in Illinois. The bedrock surface of the Tuscola area is covered by unconsolidated glacial deposits of the Pleistocene Series, consisting of soils, sands, gravels, and boulders. Pleistocene sediment thickness increases on the flanks of the Tuscola anticline. This increased thickness is a result of glacial infill of two major streams that drained to the northwest. Pleistocene sediments on the crest of the anticline are up to approximately 100 feet in thickness and lie unconformably upon Silurian and Devonian age rocks. Sediment on the flanks rests on Pennsylvanian bedrock and is more than 250 feet thick (Bristol and Prescott, 1968).

The ~~Cabot~~ formations at Cabot (Injection Zone—Franconia, Potosi, Eminence and Oneota Formations and the Confining Zone—Shakopee Formation) present in the injection system are situated on the east flank of a small very gently plunging, dipping, anticlinal structure, which is located immediately west of the large LaSalle Anticline. This small anticlinal feature is the northern extension of an unnamed northwest trending anticline which can be referred to as the Bourbon Anticline. This structure has been extensively explored for oil from the Mississippian's Rosiclare at the Bourbon Consolidated Oil Field about 2 miles SW of the Cabot site. A few oil wells have also been drilled to the Rosiclare on a small domal structure about 1/2 mile NE of the Cabot site.

The detailed structure contour map shown in Figure 2-26 was constructed using the subsurface information for these oil wells and the deep injection wells of the area. This structure map a is detailed part of the larger map shown in Figure 2-14. The larger map includes the structure of the Rosiclare, in an area 2 1/2 miles in diameter around the site, as well as the structural contours on top of the Galena to the NE of the site (Haye's Pool). The two sets of structural contours seem to join in a smooth manner even though the surfaces mapped are nearly 2,000 feet apart vertically.

The Cabot wells are located on the east flank of a NS-trending anticlinal feature in the Rosiclare. This structure can also be seen on the structural contour map on top of the Hunton Megagroup (Bristol and Prescott, 1968), included as Figure 2-27.

Figure 2-28 is an interpreted structure contour map on top of the Galena using controls from the deep wells around the Cabot site. The top of the Galena was selected because it can be determined from drill cuttings or openhole logs with a great deal of accuracy. The contours on the Galena duplicate almost exactly the shallower structure in the Rosiclare. Since the formational units below the Galena are essentially parallel, or vary very gradually and systematically in thickness from SE to NW, expectations are that the shallower structure reflects from the deeper formations (Shakopee, Oneota, Eminence, Potosi). Figure 2-29 is a structure contour map of the top of the injection zone using the same deep well control and generally reflects the shallow structure. Based on the formation tops of th~~t~~e Cabot Tuscola Injection Well No. 1. No. 2. and No.3, as depicted in Figures 2-26, 2-28, and 1-19, the waste injectate from the site will migrate to the northwest.

2.3.2 Oil and Gas Operations

Effects from offset oil and gas operations for the study area were reviewed to ascertain whether induced pressure from man-made activities (injection and oil and gas extraction) are expected to have a major effect on the lateral plume movement during either the operational time period or during the early portion of the 10,000-year time plume drift period for the Cabot facility.

The area around the Cabot plant site was an active area for oil exploration in the 1960's. The Hayes Oil Field, located approximately five miles northeast of the Cabot site, was discovered in 1962. Oil was produced from the Ordovician Galena Group at a depth of approximately 1,040 feet which is considerably shallower than the Cabot Injection (~ 4,470 feet) or Confining Zone (~ 4,125 feet) formations. Production has since declined, and the field has been essentially abandoned.

Approximately 3 miles to the southwest of the Cabot site is the Bourbon Consolidated Field. Oil is produced from the Mississippian Aux Vases, Spar Mountain, and McClosky sandstones and limestones. Depth of oil production ranges from approximately 1,512 feet to 1,980 feet which is also at depths considerably shallower than the Cabot Injection (~ 4,470 feet) and Confining Zones (~ 4,125 feet).

2.3.3 Stratigraphy of Injection and Confining Layers

Prior to the drilling and installation of Cabot Injection Well No. 3, only very limited well data and core information was available from the earlier Cabot wells. The stratigraphy at the site was derived from area well logs and literature concerning geology and oil production in the Tuscola area. Cuttings and core data that were obtained from Well No. 3 agreed well with the data from other sources documenting the local stratigraphy. Figure 2-30 is a stratigraphic column depicting Cabot's defined Injection Zone, Injection Interval, Containment Interval, and Confining Zone. Figure 2-31 is a stratigraphic cross-section that provides the typical thickness and continuity of the formations near the Cabot site.

The subsurface geology beneath the Cabot facility is described using site specific well log and core data from the injection wells and regional data. The following sections summarize the lithologies of the geological units penetrated by Well No. 3. The lithology of the units is described, with the specific cored intervals where cores were cut and recovered. The lithologies correspond well with those previously described from other wells in the area and from area geological literature.

2.3.3.1 Injection Zone

The Cabot Injection Zone consists of the Cabot Injection Interval into which waste fluids can be directly emplaced and the immediate overlying containment interval which serves to confine and arrest potential vertical fluid movement, but which are permitted to contain waste within the 10,000 year No-Migration Petition demonstration. The Injection Zone extends from approximately 4,472 feet to 5,400, referenced to Cabot Well No. 2 at the Tuscola facility. The Injection Zone is further divided into two units, the Injection Interval and the Containment Interval. The lower Oneota, Eminence, Potosi, and uppermost portion of the Franconia Formations, from approximately 4,778 feet to 5,400 feet, referenced to the Cabot Well No. 2, provides an effective injection interval in terms of its petrophysical characteristics, mineralogical composition, and areal extent. This interval has sufficient porosity, permeability, thickness, and lateral continuity to readily accept and contain injected fluids. The overlying aquiclude layers of the Uppear Oneota Formation form the Containment Interval, located at a depth of 4,472 feet to 4,778 feet (Cabot Well No. 2). The Containment Interval provides the primary containment to keep injected injected fluids within the Injection Zone.

2.3.3.2 Injection Interval

The Cabot Injection Interval (gross section) consists of the following formations, Franconia, Potosi, Eminence, and Oneota, grading from the basal section where all Injection Wells are completed to the top of the interval. The effective injection interval is apparently limited to the Franconia, Potosi, and Eminence Formations.

Franconia Formation

Approximately 27 feet of the Franconia Formation appears to have been penetrated by Well No. 3, based on correlation with the Well No. 1. However, no distinct change in lithology description from the overlying Potosi Dolomite was noted from the drill cuttings.

Potosi Formation

The Potosi Formation is approximately 189 feet thick and is a brown to light brown, tan or cream colored stylolitic, oolitic dolomite with small amounts of light grey dolomite. It is very fine to finely crystalline with traces of chert, glauconite, and pyrite throughout, and is slightly sandy near the upper contact, but gradational upward into the Eminence Formation.

Eminence Formation

The Eminence Formation is 157 feet thick and is described as a brown, light brown to cream colored sandy (fine grained) dolomite with traces of light grey dolomite. It has a very fine to finely crystalline matrix with traces of medium crystalline dolomite and exhibits small amounts of light brown translucent chert and green shale laminations with traces of pyrite and stylolites present.

Cores #5 and #6 – Injection Well No. 3

Cores #5 and #6, recovered during the drilling of Cabot Injection Well No. 3 from 4,980 to 4,996 feet and 5,010 to 5,013 feet, were located within the Eminence Formation. These can be described as a fine to medium crystalline, cherty, silty dolostone with features that include burrowed, stylolitic clay rich laminations, some stepped fractures, rare intercrystalline porosity, with slight vugular porosity, graded siliciclastic sand laminae, and argillaceous in part near the base.

Oneota Formation

The Oneota Formation is approximately 139 feet thick within the Cabot Injection Interval but also consists of 311 feet within the overlying Containment Interval (450 feet overall). It can be described as light grey to light brown or cream dense to microcrystalline dolomite with thin lenses of fine to medium, occasionally coarse grained white to clear sandstone. Features include traces of white chert, thin laminated zones of green shale with pyritic, oolitic, stylolitic, and argillaceous portions throughout.

2.3.3.3 Containment Interval

Oneota Formation

The Oneota Formation is approximately 311 feet thick within the containment interval The drill cuttings description is similar to that provided above for that portion of the formation present within the Cabot Injection Interval.

Core # 4 –Injection Well No. 3.

Core # 4 was recovered from Cabot Injection Well No. 3 from a depth interval of 4,760 to 4,786 feet within the Oneota Formation (located at the base of the Cabot Containment Interval). This was described as a medium to coarsely crystalline dolostone, cherty, vuggy, stylolitic, burrowed, greenish intercalated clay in places with shaley laminae near the base. Features include rip up clasts of chert common near the top of core, and may be classed as a dolomitized grainstone in part.

2.3.3.4 Confining Zone

Shakopee Formation

The Shakopee Formation is approximately 350 feet thick. No sandy zone was recorded near the base in cuttings or core, which would represent the New Richmond Formation. The Shakopee Formation is described as a light to medium grey, tan or light brown, dense to microcrystalline dolomite. The formation is occasionally silty with traces of pyrite, green shale laminations, and white to grey chert. The unit becomes sandier in the upper portions and appears to be slightly gradational upward into the St. Peter Formation. Two cores were recovered from the Shakopee Formation.

Core # 3 – Injection Well No. 3.

Core # 3 was recovered from Cabot Injection Well No. 3 from a depth interval of 4,430 to 4,454 feet, from the base of the Cabot Confining Zone. This is described as a finely crystalline to rarely medium crystalline, dolomitized lime mudstone. Features include relatively heavily burrowed zones with differential digenesis along burrows. There are also occasional horizontal laminations with low amplitude stylolites, cherty with rare pyrite and some discontinuous pyrite healed fractures (indistinct and discontinuous fractures) noted near the base of the cored interval.

Core # 2 – Injection Well No. 3

Core #2 was recovered from Cabot Injection Well No. 3 from a depth interval of 4,140 to 4,162 feet in the upper portions of the Shakopee, near the top of the Cabot Confining Zone. This is described as a dolostone derived from variable original lithologies, ranging from lime mudstone through packstone/wackestone to coarse grainstone. The interval is only very slightly argillaceous, containing numerous rip up clasts, abraded bioclasts, stylolites, occasional irregular fractures, and silty-sandy laminae. Some zones of intercalated greenish clay contorted by compaction are also present.

2.3.3.5 Formations Overlying the Confining Zone

St. Peter Formation (Ancell Group)

The St. Peter Formation is approximately 149 feet thick. It is described as clear to white, occasionally light grey, frosted very fine to medium, occasionally coarse sandstone. Grains are sub-angular to sub-rounded, moderately sorted, mostly consolidated but occasionally unconsolidated, slightly dolomitic with traces of pyrite, argillaceous materials and carbonaceous specks. Increasing amounts of dolomite upward toward the contact with the overlying Joachim.

Joachim Formation (Ancell Group)

The Joachim Formation is approximately 133 feet thick and can be described as brown or light brown to light grey, micritic to finely crystalline limestone with stylolitic, pyritic and carbonaceous specks. In the lower 30 percent of the unit it becomes more sandy and dolomitic.

Platteville Group

The Platteville Group is approximately 272 feet thick. It is described as a light brown or buff to light grey, cryptocrystalline to very finely crystalline, dolomitic limestone. Characteristics include fossiliferous, oolitic, pyritic, stylolitic with carbonaceous laminations with the lower one-third of the formation being notably more dolomitic than the upper two-thirds.

Decorah Formation (Galena Group)

The Decorah Formation is approximately 30 feet thick. It is described as a brown or light brown to light grey, very finely crystalline limestone, pyritic, with carbonaceous specks, oolites, stylolites, and grey shale laminations.

Kimmswick Formation (Galena Group)

The Kimmswick Formation is approximately 157 feet thick. It is described as a brown or light brown to buff, mottled, very fine to cryptocrystalline limestone. Characteristics include friable, fossiliferous, pyritic, stylolitic, with dolomite filled fractures and grey shale inclusions. It exhibits from 3 to 30 percent dull yellow fluorescence under UV light.

Scales Formation (Maquoketa Group)

The Scales Formation is approximately 83 feet thick. It is described as a grey or grey-brown to dark brown, hard limy shale, fine to medium in texture, with pyrite, carbonaceous laminations and traces of micaceous material.

Ft. Atkinson Formation (Maquoketa Group)

The Ft. Atkinson Formation is approximately 55 feet thick. It is described as a brown or light brown to buff limestone with traces of grey, hard, argillaceous, fossiliferous limestone. Characteristics include cryptocrystalline to very finely crystalline with carbonaceous specks and traces of pyrite.

Brainard Formation (Maquoketa Group)

The Brainard Formation is approximately 66 feet thick. It is described as a grey to dark grey, slightly dark brown, hard, slightly silty carbonaceous shale.

St. Clair Formation (Hunton Megagroup)

The St. Clair Formation is approximately 194 feet thick. It is described as a light brown to brown, with traces of pink, limestone with green-grey argillaceous inclusions. Characteristics include fossiliferous with traces of shale laminations, pyrite, and carbonaceous specks, being more argillaceous in the upper half and milky chert and traces of glauconite more common in the lower half of the unit.

Moccasin Springs Formation (Hunton Megagroup) - Lowermost USDW

The Moccasin Springs Formation is approximately 456 feet thick. It is described as a light brown to tan with some light grey very fine and finely crystalline to sucrosic fossiliferous dolomite. As much as 10 to 20 percent intercrystalline and vugular porosity is visible, especially in the upper two-thirds of the unit. Traces of argillaceous inclusions, pyrite, and calcite are present, and the lower half of the unit is more light grey to grey in color.

Core # 1 – Injection Well No. 3

Core # 1 was recovered from Cabot Injection Well No. 3 from a depth interval of 2,751 to 2,781 feet, near the mid-point of the formation. It is described as a light to medium grey dolostone, and is derived from variable original lithologies ranging from lime mudstones to grainstones, more commonly from bioclastic grainstones. The core is commonly fossiliferous, with encrusting bryozoans, crinoids, and other abraded bioclasts present. Occasional discontinuous fractures present with low amplitude to peaked stylolites common and intercrystalline, moldic and vuggy porosity up to 30 percent .

The Silurian age Moccasin Springs Formation at 2,700 feet has been designated the base of the lowermost USDW. This point also defines a stratigraphic level which is not breached by erosion on the Tuscola Anticline. This insures a seal and lateral continuity of all zones stratigraphically lower in the Cabot Injection sediment wedge (see Figure 2-23). Figure 2-32 is a north-south cross-section showing the generalized basal boundary of the lowermost USDW for Illinois. Cabot is very conservative in defining the base of the lowermost USDW at the injection site. The USDW is separated from the top of the Confining Zone by over 1,400 feet of various sediments, providing additional confining and buffer injection interval protection to the lowermost USDW.

Total dissolved solids (TDS) calculated from the Cabot electric logs indicate that TDS values of the connate water are greater than 10,000 mg/l below a depth of 2,700 feet. Calculations indicate that the entire Moccasin Springs Formation contains greater than 10,000 mg/l TDS, but the 2,700 feet level was selected to be conservative. Approximately 3,700 feet northwest of the Cabot Well No. 1, the U.S. Industrial Chemical Company No. 1 Well reported 14,160 mg/I TDS from the interval 2,412 feet to 2,510 feet, which includes a portion of the upper Moccasin Springs Formation. Water quality having acceptable TDS levels in the Silurian and Devonian dolomites is found at or near the bedrock surface. Water quality quickly deteriorates with increasing depth to the west, moving downdip from the anticline.

Grand Tower Formation (Hunton Megagroup)

The Grand Tower Formation is approximately 63 feet thick. It is described as brown or light brown, with traces of grey, argillaceous, very finely crystalline dolomite. Characteristics include fossiliferous, shaley, with traces of pyrite, with the lower half of the unit grading to limey.

New Albany Group

The New Albany Group is approximately 103 feet thick. It is described as dark brown to brown slightly limey shale, with traces of green shale and slightly pyritic with carbonaceous laminations.

Borden Formation

The Borden Formation is approximately 616 feet thick. It is described as grey to grayish green, very silty calcareous shale, with small amounts of light brown to brown shale. It is friable, carbonaceous, pyritic, with fine sandy lenses near the base of the unit.

St. Louis/Salem Formation

The St. Louis Formation is approximately 196 feet thick. It is described as brown to light brown, very finely crystalline, dense, sandy dolomite, carbonaceous and pyretic with occasional thin grey-green shale lenses, and the unit tends to be limey in the lower half.

St. Genevieve Formation

The St. Genevieve Formation is approximately 85 feet thick. It is described as brown to light brown, with traces of grey, cryptocrystalline limestone. The lower half of the unit is very sandy, with very fine to fine, clear to frosted sand grains.

Pennsylvanian, undifferentiated

The Pennsylvanian is approximately 1,400 feet thick. It is described as alternating limestones, sandstones, dolomites, and siltstone units, with lesser thicknesses of shale.

A limited supply of water can sometimes be obtained from these thin stringers when water cannot be obtained directly from overlying glacial till deposits. Sands and creviced limestones, such as the Pennsylvanian Mattoon Formation, may also yield small quantities of water.

Glacial sand and gravel deposits in the ~~Pennsylvanian~~ eroded bedrock valleys may provide excellent aquifers throughout east-central Illinois (Kolata, 2005). The Pesotum Valley is located north of the Cabot site, however, no prolific aquifers are reported. Glacial till also provides a limited source of water for residential and farm use in the area, with wells completed in till deposits from sand lenses averaging only 5 feet to 10 feet in thickness.

2.3.4 Injection and Confining Layers Reservoir Properties

The acquisition of reliable site specific porosity and permeability data was one of the primary objectives of the information gathering effort during the installation of Cabot's Injection Well No. 3. Modern geophysical logs run in the well provided porosity data from the geological units penetrated. Separately, porosity and permeability data were also obtained from analysis performed on whole cores recovered during the well drilling and installation. The following subsections summarize the data obtained from Cabot Injection Well No. 3.

2.3.4.1 Porosity and Permeability Data

Openhole geophysical logs that yield quantitative porosity information were run during the installation of Cabot Injection Well No. 3. These included: bulk density, compensated densilog, compensated neutron and long spaced borehole compensated acoustilog. Two Epilogs (Complex Reservoir Analysis) were computed by Western Atlas using the data from the individual density, neutron and acoustic logs run, to calculate porosity, estimated permeability, grain density and lithology. Calculations from the two Epilogs were processed over the depth intervals from approximately 290 feet to 2,750 feet, and from 2,765 feet to 5,265 feet. Table 2-2 summarizes the porosity (minimum, maximum, and average) of the geological formations based on the data computed cross plots. The values in Table 2-2 agree with the average porosity values and ranges of porosity previously calculated from the logs of Cabot’s Injection Well No. 1 and Injection Well No. 2.

2.3.4.2 Core Data

A total of 6 intervals (Cores #1 through #6), each 30 feet in length, were cored, for a gross total of 180 feet of coring during Cabot Injection Well No. 3 installation. Approximately 119 net feet of core was actually recovered. Cored intervals and footage recovered are indicated below:

Core #	Regulatory Unit	Formation	Depth Cored (ft)	Recovery

1	USDW	Moccasin	2,751-2,781	30 feet
2	Confining Zone	Shakopee	4,140-4,180	22 feet
3	Confining Zone	Shakopee	4,430-4,460	24 feet
4	Containment Interval	Oneota	4,760-4,790	25 feet
5	Injection Interval	Eminence	4,980-5,010	15 feet
6	Injection Interval	Eminence	5,010-5,040	3 feet

The approximate 89 feet of core recovered from the Confining Zone and Injection Zone (Cores #2 through #6) was subjected to detailed petrophysical testing. Core #1, from the Moccasin Springs Formation, was megascopically described but not subjected to any additional testing,

Vertical and horizontal plugs were drilled every foot from Cores #2 through #6, and prepared for routine porosity and permeability testing. Porosity, permeability to air, and grain density measurements were taken on the horizontal plugs from each cut plug foot. Permeability to brine was determined for the horizontal and vertical plugs from each foot of depth. The brine used for all liquid permeability testing was 2 percent NaCl by weight mixed with deionized water. A net confining stress of 2,650 pounds per square inch (psi) was utilized for all permeability to brine testing in order to simulate typical reservoir conditions.

Appendix 2-2 contains a summary of porosity and permeability data from core analysis compiled from the original OMNI Laboratories data. The data is subdivided into geological units, injection activity related zones and intervals, and indicate the average value for each of the sub-divided units. Values for average vertical permeability to brine listed are harmonic averages, while all other averages are arithmetic.

2.3.4.2.1 Core Mineralogy

Based on the description of the slabbed cores from Cabot Injection Well No. 3, twenty-three (23) sample points were selected which were considered representative of the variety of the core lithologies and textures. These samples were subjected to additional analysis with x-ray diffraction analysis prepared from each of the selected data points. In addition, oversize thin sections were prepared for each selected data point to describe depositional and digenetic texture of the sample and for slide mounting for petrographic examination and point counting.

Some variability between the petrographic data results and the X-ray diffraction data for the samples is present. In general, x-ray diffraction indicated a higher quartz content and the presence of several percent calcite in the samples. This led to a correspondingly lower dolomite content in the X-ray data compared to the petrographic results. Although the samples analyzed by the two methods are listed as being from the same depth, they are not actually "the same" sample, and may have been separated physically in the core formation by a distance of as much as two or three inches. These differences in the analytical results are due to a combination of natural lithologic variability, differences in sample methodology, instrumentation response, and sensitivity for the two types of methods performed.

A description of the sample methodology utilized and complete results of the petrographic and x-ray diffraction analyses were originally included in Appendix A of the Completion Report for Cabot Injection Well No. 3. The data is summarized in the following sections.

2.3.4.2.2 Petrographic Data

All twenty-three thin sections from three key geological formations the Shakopee, Oneota, and Eminence Formations were classified as dolostone. A wide variety of carbonate textures, crystal forms, porosity types, pore and fracture fillings were described from the detailed thin section examination. Forty-three photomicrographs, included in Cabot's Injection Well No. 3 Completion Report, describe the variety of lithologies and textures encountered.

Petrographic data from the core analyses from Injection Well No. 3 is included in Appendix 2-3. The data has been summarized from the original information provided by OMNI Laboratories. The data is subdivided into geological units and injection activity related zones and intervals. A brief summary of the mineralogy is listed below:

<u>Shakopee (Confining Zone)</u>

Nine samples from the core averaged 96.6% authigenic material, 1.5% framework grains, 0.1% detrital matrix, and 11% porosity.

Oneota (Containment Interval)

Six samples from the core averaged 92.9% authigenic material, 1.1% framework grains, 0.5% detrital matrix, and 5.6% porosity.

Eminence (Injection Interval)

Eight samples from the core averaged 94.1% authigenic material, 2.4% framework grains, 2.4% detrital matrix, and 0.8% porosity.

For the three formations examined, the authigenic material consisted of predominately dolomite with minor amounts of clay, quartz, pyrite, and ankerite (as pore or fracture filling). The framework grains were predominately quartz with lesser amounts of feldspar. Observed porosity was mostly microscopic variety, followed by lesser amounts of intercrystalline and vugular porosity.

2.3.4.2.3 X-Ray Diffraction Data

Appendix 2-4 contains X-ray diffraction data summarized from the original core analysis results provided by OMNI Laboratories. The data is subdivided into geological units, injection activity related zones and intervals, and indicates the arithmetic average data for each of the subdivided units.

Shakopee (Confining Zone)

Nine samples from the core averaged 84.4% carbonate material, 3.7% clays, and 12.7% other minerals.

Oneota (Containment Interval)

Six samples from the core averaged 68.3% carbonate material, 2.0% clays, and 30.3% other minerals.

Eminence (Injection Interval)

Eight samples from the core averaged 89.4% carbonate material, 1.8% clays, and 9.3% other minerals.

For each of the above geological units, the carbonate materials consisted of over 95% dolomite, the clay was primarily illite, and other minerals which were mostly quartz and feldspar.

2.3.4.3 Containment Interval Properties

Immediate containment for the Cabot Injection Interval (Franconia, Potosi, Eminence, and Oneota Dolomites) is provided by continuous buffers and thick sections of the overlying Oneota Dolomite Formation. This section within the Oneota is designated the Containment Interval. These formations consist of argillaceous dolomite section with interbeds of sandstone, shale and siltstone, all of which serve to provide containment for the deeper Injection Interval in the area (see Figure 2-30 for depths in each well). This thickness is more than adequate to contain any potential worst-case modeled vertical waste movement over a 10,000-year time frame (see Section 3.0).

2.3.4.3.1 Oneota Formation

The upper portion of the Oneota Formation serves as the major Containment Interval for the underlying Injection Zone. The Containment Interval is defined as the 306-foot interval (Cabot Well No. 2) overlying the top of the Injection Zone. The Oneota Formation, as determined from recovered core, is predominantly dolostone with intercalated clay present and shaley laminae near the base of the formation. Based on vertical caprock analysis from core obtained from Cabot's Injection Well No. 3, the permeability of the Oneota Dolomite (Containment Interval) is 1.7×10^{-5} millidarcies with 3.8 percent porosity, and horizontal permeability measured at 5.67×10^{-3} millidarcies.

2.3.4.4 Confining Zone

Overlying additional containment supplemental to the immediate Containment Interval above the Cabot Injection Zone (Franconia, Potosi, Eminence, and Oneota Dolomites) is provided by continuous buffers and thick sections of theoverlying Shakopee Dolomite Formation which is designated as the Confining Zone. This formation consists of argillaceous dolomite sections with interbeds of sandstone, shale, and siltstone all of which serve to provide containment for the deeper Injection Interval in the area. Figure 2-33 is a stratigraphic cross section showing the confining zone from the Cabot site to the Tuscola Anticline.

2.3.4.4.1 Shakopee Formation

The Shakopee Dolomite is defined as the Confining Zone, extending from a depth of approximately 4,125 feet to the top of the Injection Zone at approximately 4,472 (Cabot Well No. 2). The unit is continuous and thickens to the southeast only slightly, while maintaining its argillaceous character, with interbeds of chert, minor sandstone, shale, and siltstone. These interbeds are considered favorable for mitigating any potential upward waste migration from the Injection Interval. The clay sections and argillaceous characteristics would act as direct barriers to flow, while permeable minor sand interbeds would offer classic buffer intervals to allow for pressure and fluid migration relief. Based on vertical caprock analysis from core obtained from Cabot's Injection Well No. 3, the permeability of the Shakopee Dolomite (Confining Zone) is 1.1 x 10-5 millidarcies with 3.7 percent porosity, and horizontal permeability measured at 4.53 x 10-1 millidarcies. The reservoir properties and interval thickness demonstrate that this section can confidently be designated Cabot's Confining Zone.

2.3.4.5 Additional Overlying Confining Formations

Additional formations exist overlying the Shakopee Dolomite, such as permeable and impermeable formations. Immediately above the Shakopee Dolomite, from deeper to shallow depths, the following formations provide approximately 867 gross feet of buffer above the Confining Zone, providing additional backup containment:

Buffer permeable interval:

St. Peter Formation—149 feet thick, sandstone, dolomitic in part with argillaceous material

Confining formations:

Joachim Formation—133 feet thick, dense crystalline limestone, slight sandy and dolomitic at the base

Decorah Formation—30 feet thick, fine crystalline limestone with grey shale laminations

Kimmswick Formation—157 feet thick, fine-cryptocrystalline limestone with grey shale inclusions

Scales Formation—83 feet thick, hard, limey shale

Ft. Atkinson Formation—55 feet thick, hard, argillaceous, fossiliferous limestone

Brainard Formation—66 feet thick, hard, carbonaceous shale

St. Clair Formation—194 feet thick, limestone, with argillaceous inclusons, shale laminations, with chert

This thickness is more than adequate to contain any potential worst-case modeled vertical waste movement over a 10,000-year time frame (see Section 3.0).

2.4 HYDROGEOLOGY

2.4.1 Regional Hydrogeology

The bedrock of east-central Illinois has limited potential for providing acceptable levels of drinking water (Hanson, 1950). Only where the bedrock is at or near the surface can water with acceptable TDS quality levels can be found. Normally below depths of 200 to 400 feet, the water becomes too highly mineralized for public usage. Along the trace of the La Salle Anticlinal Belt, (Nelson, 1995) older more permeable rocks can be found near the surface and are capable of producing water of good quality. However, quality quickly deteriorates with depth. Figure 2-34 is a north-south and northwest-southeast cross-section of the state showing TDS values of formation waters. Unfortunately, water from the shallow bedrock is usually only available in small quantities, where fractured limestone and permeable sandstone is encountered. Since most of the bedrock surface in east-central Illinois (Kolata, 2005) is found at depths that contain highly mineralized water, an alternate water supply is needed. Groundwater localized within glacial deposits, which lie on top of the bedrock, provide the bulk of water supplies for farms and residences in the Tuscola area. The hydraulic conductivity of glacial aquifers is highly variable in shallow deposits, but tends to increase and become less variable with depth (Kempton et. al., 1982). Groundwater movement within glacial deposits and the underlying bedrock is very slow (Piskin and Bergstrom, 1975). A shallow monitoring well program at the Cabot plant determined that regional groundwater flow in the glacial till deposits is to the south-southeast. A copy of the shallow monitoring well program is included as Appendix 2-8, and represents the historical monitoring program, which has evolved with some of the original monitor wells plugged. Presently the current program uses a limited number (6 site monitor wells) to monitor a horizon at 60-feet. A description of the current program is described below:

> The shallow monitoring well program data is taken from: *Assessment of Fourth Quarterly (Annual 1991) Collected Groundwater Samples, Closed RCRA Impoundment, Cabot Corporation Plant, Tuscola, IL*, prepared by Hydropoll, Inc. in December 1991. A total of 25 wells are present on the plant grounds. Of this total, 19 are included in the monitoring system for the closed impoundment as approved by the Illinois Environmental Protection Agency. Nine wells are completed in the weathered till at

depths of 20 to 30 feet, five wells are completed in a deeper sand unit in the till at approximately 100 feet, four wells are completed in the till at depths of 50 to 75 feet, and one deeper well drilled to a depth of 212 feet and screened in a silt from 199 to 203 feet. Four wells of the 19 total are located singly and 15 are located in multiple well clusters. One of the clusters is located upgradient and the remaining five clusters is located down gradient of the closed impoundment.

Potentiometric maps were constructed from the water level data in the weathered till and in the deeper sand unit. The potentiometric surface map of the shallow groundwater showed the direction of the regional groundwater flow. The regional flow is to the southeast. A groundwater divide, across which no flow occurs, is located just north of the closed impoundment. The divide prevents flow of groundwater from the closed impoundment. The calculated field hydraulic conductivity in the shallow weathered till was 62,1 ft/year. Effective porosity of the weathered till is estimated to be 0.10. A groundwater velocity of 4.0 ft/yr was calculated using these values.

Water levels in the deep sand did not vary significantly between the wells. A water level difference of only 0.57 feet was measured between the wells. The water flow direction within the deeper sand was tentatively determined to be to the west. Field hydraulic conductivity was determined as 3400 ft/yr. Effective porosity of the deep sand is estimated as 0.20. A groundwater velocity of 42.5 ft/yr was calculated using these values.

Water level differences in the well clusters indicated that the groundwater moves downward between the shallow till wells and the deep sand wells in the same cluster.

Prior to the continental glaciers, erosion had altered the bedrock surface. Well developed drainage patterns resulted in the region. Afterwards, glaciers deposited debris across the bedrock surface. Glacial debris such as sand, gravel, and boulders are important bedrock valley fill for potential sources of large groundwater supplies in the state.

Glacial deposits of east-central Illinois are assigned to three stages of continental glaciation, Kansan, Illinoian, and Wisconsin (Piskin and Bergstrom, 1975). Three formations evolved from each period: the Banner, Glasford, and Wedron. Each of these formations has several members composed of glacial tills, outwash, or a combination of both. Glacial deposits covering the bedrock surface in this region may range from a few feet to more than 400 feet.

2.4.1.1 Bedrock Aquifers

In Douglas County, limited quantities of fresh water are obtained from bedrock aquifers. Pennsylvanian bedrock underlies the glacial drift in most of the county (Kolata, 2005). Although the Pennsylvanian is mostly shale, thin beds of limestone and sandstones are also found interbedded which might provide a limited local source of fresh water. Along the anticlinal belt where bedrock lies near the surface, fractured dolomites of Silurian and Devonian age also provide acceptable levels of drinking water.

2.4.1.2 Sand and Gravel Aquifers

2.4.1.2.1 Banner Formation Aquifer

The Banner Formation of east-central Illinois ~~is~~includes a ~~comprised of a~~ thick, extensive sand member, the Mahomet Sand Member. This membere ~~Mahomet~~ is a valley train deposit which may be over ~~400~~150 feet thick and is composed of clean sand, gravel, and minor amounts of silt and clay. The deposit grades upward into sands and silts with water yields greatly reduced along valley margins, where thicknesses may be 50 feet or less. In DeWitt County, municipal and industrial water supplies are obtained from the Mahomet. Figure 2-35 includes cross-sections showing the sand and gravel aquifers in the area.

2.4.1.2.2 Glasford Formation Aquifer

The main member of the Glasford Formation is the base of the Vandalia Till. At shallower depths, an aquifer can be found between the Radnor and Vandalia Till Members (see Figures 2-35). Thicknesses of the Glasford Aquifer in the east-central portion of the state range from 5 feet to over 60 feet. It is believed that areas of greater thicknesses may be the result of two units overlying each other. In Douglas County, the Glasford is an important aquifer with distribution and thickness less predictable than the Banner Formation.

2.4.1.2.3 Wedron Formation Aquifer

The principal aquifer of the Wedron Formation is the Ashmore Aquifer consisting of an outwash sand and gravel averaging 10 feet in thickness. At some sites, thicknesses of 50 feet have been reported. In the northeast corner of the state, the Wedron is well developed, and small municipal supplies of water are obtained.

2.4.1.2.4 Surficial Aquifers

The Henry Formation consists of surficial sand and gravel found as narrow deposits with thicknesses that may range from a few feet to as much as 50 feet. The formation is more developed and thickest along river valleys, and successful wells are relatively shallow.

2.4.2 Local Hydrogeology

2.4.2.1 Bedrock Aquifer

The bedrock formations of the Tuscola area are comprised of limestones, dolomites, sandstones, and shales. These formations are not recognized as major aquifers due to their high TDS levels; unless they are found near the surface and fracturing is sufficient to produce large quantities of fresh water. For over 50 years, the city of Tuscola utilized wells completed in the Silurian dolomite for public water supply. These wells were typically openhole completions in the Niagran Formation at depths below 400 feet. The well yields from these wells were generally less than 200 gallons per minute with varying water level drawdowns of 40 to 100 feet in specific wells (ISGS, 1950). Approximately 3 miles east of the Cabot site, Devonian and Silurian rocks are found near the surface on the Tuscola Anticline (Figure 2-36). The deepest water producing well on record in the area was completed in 1897, at a depth of 3,017 feet, and was located in the western portion of Tuscola, 2,075 feet FNL and 750 feet FWL of Section 34, T6N R8E. This location is apparently 13,250 feet from Cabot Injection Well No. 2 (~2.51 miles) and outside the Area of Review (AOR). Originally, the well was to be completed in the Mt. Simon Formation, but it is doubtful that the Mt. Simon was ever reached. Unfortunately, only a partial drillers log was available, and it is not known what formation the well was completed in. Analysis of a water sample taken from the well reported 139 parts per million (ppm) hardness, 964 ppm mineral content, and 1.6 ppm iron content. The well was capable of producing 50 gallons per minute (gpm), and its use was discontinued in 1916. The well was plugged and abandoned in 1951, by filling the hole with gravel from TD to 50 feet, and filling the top 50 feet with grout (John S. Nealon, ISWS, written communication, 1986). The location of this well is reportedly beneath a building currently housing an antique business.

Water bearing formations deeper than the Silurian increase in TDS values with depth. Figure 2-37 includes isoconcentration maps of brines in the Ordovician "Trenton" (Kimmswick, Galena) and St. Peter Formations.

Within the AOR, the USI No. 1 Well measured a TDS of 18,125 ppm from a drill stem test over the interval 2,412 feet to 2,510 feet, which correlates to the Devonian and the upper section of the Silurian. The Silurian and Devonian formations are believed to be hydrologically connected.

2.4.2.2 Sand and Gravel Aquifers

Within the 2.0-mile radius Area of Review (AOR), freshwater is obtained from various shallow sand and gravel deposits. In the northwest and central part of the county, these deposits are more consistent and up to 150 feet thick in the buried Pesotum Valley. Figure 2-38 is a map of the bedrock topography, showing location of the Pesotum Valley. A small tributary of the buried valley can be found near the Cabot plant site.

Hydraulic conductivity was measured historically in shallow monitoring wells at the Cabot plant. Vertical hydraulic conductivity averaged 8.3 x 10^{-9} centimeters per second (cm/sec) with horizontal conductivity ranging from 5.8 x 10^{-5} to 6.6 x 10^{-5} cm/sec based on two field measurements.

2.4.3 Determination of the Lowermost USDW

Total dissolved solids have previously been calculated from the Cabot Injection Well No. 1 electric logs, indicating that TDS values of connate water are greater than 10,000 milligrams per liter (mg/l) below a depth of 2,700 feet. Calculations indicate that the entire Moccasin Springs Formation contains greater than 10,000 mg/l TDS, but the 2,700 foot level was selected for the base of the lowermost USDW to be conservative. Appendix 2-5 includes the TDS calculations.

Prior to the installation of Well No. 3, the lowermost USDW was conservatively calculated to be within the Moccasin Springs Formation at a measured depth of 2,700 feet, based on the interpretation of geophysical logs. To be considered an USDW, a formation must be capable of yielding a volume of water suitable for a public water supply, and must contain reservoir fluid with less than 10,000 mg/l total dissolved solids.

During the installation of the Cabot Injection Well No. 3, numerous attempts were made to recover formation fluid samples from intervals within the Moccasin Springs and from other shallower formations for the determination of total dissolved solids content. Appendix 2-6 includes a listing of the intervals in which testing was attempted. The shallowest interval from which a fluid sample was successfully recovered was 1,632-1,642 feet, from the St. Louis/Salem Formation. This sample of reservoir fluid was laboratory tested and found to contain total dissolved solids of 22,200 mg/l. All formation fluid samples recovered from deeper zones were also determined to contain in excess of 10,000 mg/l total dissolved solids, therefore defining the lowermost USDW.

During purging of the intervals to be sampled, fluid recovered at the surface was monitored for conductivity, pH, and temperature using hand held field meters. Conductivity is converted to an equivalent TDS measurement by using a multiplication factor of between 0.55 and 0.70 (assuming primarily inorganic constituents in solution). The stabilized values for the parameters from each shallow zone are listed below, with the conversion to TDS utilizing a factor of 0.625.

Depth (ft)	Calculated TDS (mg/l) (using 0.625 factor)	Conductivity (mS)	pH	Temp (ºF)
1,632-1,642	21,625	34,600	7.44	71
2,625-2,662	14,750	23,600	6.87	70
2,751-2,761	16,750	26,800	8.22	75

For analysis performed from electric logs, the "m" cementation exponent is very important. Porosity can be related to resistivity by the formation resistivity factor relationship, but the difficulty is the conversion factors "m" and "a" used in the equation. Special core analysis to determine "m" is performed on a very limited basis. The relationships of carbonates and sandstones that are generally used are empirically derived from a large population of data.

Cementation affects the shape or geometry of the pore throats, and the constrictions, changing diameters, and shapes of pore tunnels all relate to the "m" factor. The numerator "a" of the formation factor relationship is considered to be representative of tortuosity. The formation resistivity factor relationship is as follows :

$F_r = a/ø^m$ from Schlumberger, 1989, eq. 2-2

where

F_r is the formation resistivity factor,
"a" is a tortuosity value,
"m" is the cementation factor and
"ø" is a decimal fraction for porosity.

Typical values used for indurated carbonate rocks are a=1 and m=2. The formation resistivity factor can also be used in the following relationship:

$R_{wa} = R_t/F_r$ from Schlumberger, 1989, eq. 4-5

where

R_{wa} is apparent formation fluid resistivity and
R_t is the total formation resistivity measured from a deep reading induction log.

Combining these two equations yields:

$Rwa = (R_t \times ø^m) / a$

Based on the total dissolved solids contents (and corresponding calculated fluid resistivities) of the recovered formation fluid samples from depths of 2,751-2,762 feet, 2,652-2,662 feet and 1,632-1,642 feet in the Cabot Injection Well No. 3, calculations to solve for "m", and utilizing "a" = 1 were performed using the above equations with resistivity and porosity values determined from geophysical logs of Injection Well No. 3. These calculations indicated that cementation factors "m" of 3.0, 4.1 and 2.35, respectively, would be necessary in order for the theoretical values to approximate the laboratory measured values of TDS. These cementation factors represent average values for m.

In order to evaluate the geological formations shallower than 1,632 feet in Injection Well No. 3, a cementation factor of 2.4 was utilized for log calculations, since it closely approximates the value obtained for the 1,632-1,642 foot fluid sample and to be conservative (a higher value used for m in the calculations tends to increase the determined TDS value). A formation fluid temperature of 70°F was assumed for all calculations. The results of calculations of total dissolved solids content of shallow formations were performed using the Cabot Injection Well No. 3 geophysical logs and are shown in Appendix 2-5. This data indicates that the interval at approximately 1,012-1,022 feet (Pennsylvanian) is the deepest formation zone present with less than 10,000 mg/l total dissolved solids as calculated from logs.

To remain conservative, Cabot will continue to designate the Moccasin Springs Formation at a depth of 2,700 feet as the lowermost USDW at the Cabot site. This conservative designation of the lowermost USDW will provide for additional protection. The actual lowermost USDW is at least 950 feet shallower, thereby placing additional hydro-geological barriers and buffers between waste contained in the Cabot Injection Zone (~4,100 feet), and any potentially usable shallow water supply sources in the area.

Due to limited data availability, it is not possible to map the lateral and vertical limits of formation waters with TDS values of 10,000 ppm or less. However, based on the data present, it can be assumed that the TDS levels increase with depth in the Tuscola area from the estimated depth of the lowermost USDW (~2,700 feet). Water analysis reports from other wells in the area also indicate that the TDS levels are well in excess of the 10,000 ppm values in the deep Injection Interval of the Cabot injection wells.

The direction of local groundwater flow is believed to be to the southwest (if influenced by the presence of Tuscola Anticline).

2.4.4 Potentiometric Surface of the Lowermost USDW

Testing during the installation of Cabot Injection Well No. 3 yielded data on the pressure and fluid characteristics of the Moccasin Springs Formation. Formation testing between 2,751 feet and 2,762 feet (RKB) indicated a pressure of 1,132.2 psi at 2,733 feet (RKB). The rotary kelly bushing (RKB) reference point for this well was +706 feet mean sea level (msl). Fluid with 22,600 mg/l total dissolved solids was recovered from the tested interval. Assuming a specific gravity of 1.012 for the fluid, the column that could be supported can be calculated as follows: 1,132.2 psi / (0.433 psi/ft x 1.012) = 2,646 feet. The top of a column of formation fluid 2,646 feet above the 2,733 foot (RKB) reference measurement point would be present at an elevation of +619 feet (msl).

2.4.5 Potentiometric Surface of the Aquifer Overlying the Confining Zone

The first aquifer that overlies the confining zone is the St. Peter Sandstone formation between depths of 3,968 feet and 4,117 feet (RKB). Testing during the installation of Cabot Injection Well No. 3 yielded data on the pressure and fluid characteristics of the St. Peter Formation. Formation testing between 3,960 feet and 3,993 feet (RKB) indicated a pressure of 1,640 psi at 3,976.5 feet (RKB). Fluid with measured specific gravity of 1.01 was recovered from the interval. The column that could be supported can be calculated as follows:

1,640 psi / (0.433 psi/ft x 1.01) = 3,750 feet.

The top of a column of formation fluid 3,750 feet above the 3,971.5 feet (RKB) reference measurement point would be at an elevation of +479.5 feet (msl).

2.4.6 Groundwater Quality

As noted earlier, freshwater from the bedrock formations deteriorates in quality quickly with depth. Low TDS concentration water was found only where the bedrock was located near the surface. Other groundwater sources for local farms and rural areas are aquifers found in shallow glacial deposits. The City of Tuscola previously obtained a portion of its water supply from wells, but these wells have all been plugged and abandoned since 1997, and the city now obtains water from a commercial supplier. The following table lists the depths of these now plugged wells and their corresponding water quality:

Well No.	Date Drilled	Depth (ft)	Hardness (ppm)	Residue (ppm)	Iron (ppm)
1	1916	287	*	*	*
2	1916	300	232	353	0.5
3	1931	523	*	*	*
4	1946	694	246	412	0.5
5	1948	553	243	498	0.6
6	1956	460	*	*	*
7	1958	557	*	*	*
8	1959	500	*	*	*

* No test reported

Formation fluid samples were recovered from a total of six (6) zones in Cabot's Injection Well No. 3. The fluids recovered from the shallowest of the three intervals sampled were only analyzed for total dissolved solids, in an attempt to better define the depth of the lowermost USDW. Fluids recovered from the three deepest intervals sampled were subjected to considerably more comprehensive analysis, to characterize the formation water chemistry. The more comprehensive suite of parameters consisted of analysis for common ground water constituents, physical properties, metals, volatile organic compounds, semi-volatile organic compounds, inorganic compounds, pesticides and PCBs. The analytical results for all of the water analyses are reproduced in Appendix 2-7. The intervals from which representative fluid samples were recovered are listed in the table below.

MEASURED DEPTH (ft)	GEOLOGICAL UNIT	TDS VALUES (Mg/l)	ANALYSIS PERFORMED
1,632-1,642	St. Louis/Salem	22,200	TDS Only
2,652-2,662	Moccasin Springs	14,200	TDS Only
2,751-2,761	Moccasin Springs	22,600	TDS Only
3,960-3993	Joachim/St. Peter	12,300	Comprehensive Analysis
4,430-4,460	Shakopee/Oneota	17,600	Comprehensive Analysis

4,608-4,750	Oneota	19,900	Comprehensive Analysis

2.5 SUMMARY

The analysis of regional and local geology near the Cabot Tuscola Plant demonstrates that the plant is well-sited for waste injection. The suitable and favorable dolomites of the Franconia, Potosi, Eminence and Oneota Formations provide an effective injection reservoir in terms of lateral extent, mineralogical composition, and petrophysical characteristics. The reservoir into which waste is injected has suitable permeability, porosity, thickness, and lateral continuity to accept and contain injected fluids. The acidic injectate from Cabot has greatly enhanced the native permeability, likely utilizing dissolution of carbonate cement in the dolomite and dolostone intervals to yield very favorable injection interval matrix reservoir permeability and transmissivity.

The overlying aquiclude layers in the Oneota Formation are dense, and of sufficient thickness to act as impermeable vertical barriers, while being laterally continuous to contain the injected fluids in the injection zone. Additionally, minor shales of the overlying confining intervals and buffer permeable intervals act as secondary protection for potential vertical migration.

The thick overlying formations extend laterally across the region and are well over 1,000 times less permeable than the underlying injection reservoirs. The existence of multiple formation layers between the top of the Cabot Injection Zone (~4,472 feet) and the base of the lowermost USDW (~ 2,700 feet) ensure additional protection of USDWs.

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APPENDIX 2-1

NATIONAL GEOPHYSICAL DATA CENTER &

NATIONAL EATHQAUKE INFORMATION CENTER – EARTHQUAKE DATA

APPENDIX 2-2

CORE ANALYSIS AND PERMEABILITY DATA

CABOT INJECTION WELL NOS. 1 AND 3

APPENDIX 2-3

CORE ANALYSIS – PETROGRAPHIC DATA

CABOT INJECTION WELL NO. 3

APPENDIX 2-4

CORE ANALYSIS – X-RAY DIFFRACTION DATA

CABOT INJECTION WELL NO. 3

APPENDIX 2-5

USDW DETERMINATION

CABOT INJECTION WELL NO. 3

APPENDIX 2-6

FORMATION TESTING SUMMARY

CABOT INJECTION WELL NO. 3

APPENDIX 2-7

FORMATION FLUID ANALYSIS RESULTS

CABOT INJECTION WELL NO. 3

APPENDIX 2-8

CABOT SHALLOW MONITORING PROGRAM

ASSESSMENT OF FOURTH QUARTERLY (Annual 1991)

Collected Groundwater Samples, Closed RCRA Impoundment,

Cabot Corporation Plant, Tuscola, IL,

prepared by Hydropoll, Inc. December, 1991

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Tuscola - Douglas Co., IL

2007 HWDIR EXEMPTION PETITION REISSUANCE

Response to EPA NODs of 5-22-08

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2007 Petition for Renewal of Exemption from the Land Disposal Restrictions

Responses to EPA Petition Comments & Deficiencies

May 22, 2008

-- Technical Responses

-- Replacement Pages,Tables, Figures & Appendices

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September 30, 2008

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CABOT TUSCOLA, IL
Response to
EPA PETITION COMMENTS AND DEFICIENCIES May 22, 2008

INDEX OF REPLACEMENT AND NEW PAGES

Page 3-63 **Revision to 2027 Plume extent**
Page 3-64 **Revision to 2027 maximum Pressure, vertical extent**
Page 3-67 **Revision to 2057 vertical extent**
Page 3-70 **Revision on dispersion effects.**
Page 3-71 **Revision to dispersion discussion.**

Attachments

Attachment 1 **Structural Features in Illinois and Seismic Reflection Profile through Charleston Monocline with location of Cabot Facility (adapted from ISGS Bull. 100, W. John Nelson).**

Attachment 2 **Major Structural Features in Illinois and Regional Setting (adapted from ISGS Bull. 100, W. John Nelson).**

Replacement Tables

Table 3-4 **Comparison of Model Inputs – 1990 Cabot Petition and 2007 Renewal**

Table 3-9 **Cabot Potosi-Eminence Dolomite Injection Interval Summary of Base Case – Model Inputs and Results**

Replacement Figures

Figure 2-1 **Stratigraphic Column of Cabot Site**

Figure 3-13 **Model Calibration—Comparison of Model Predicted vs. Measured Pressure Increase – Well 1**

Figure 3-14 **Model Calibration—Comparison of Model Predicted vs. Measured Pressure Increase – Well 2**

Figure 3-15 **Model Calibration—Comparison of Model Predicted vs. Measured Pressure Increase – Well 3**

Figure 3-16 **Conservative Operational Plume Boundary at Year-End 2006, due to Injection into the Potosi-Eminence Injection Interval, Base Case, h=280', porosity=4%, M=2.54.**

Figure 3-17 **Conservative Operational Pressure Increase at Year-End 2006, due to Injection into the Potosi-Eminence Injection Interval, Base Case, h=280', porosity=4%, Maximum Pressure Increase is 8.6 psi at Injection Well No. 3.**

Replacement Appendices

CITED REFERENCE APPENDIX – COPIES OF PERTINANT PAGES

CABOT TUSCOLA, IL
EPA PETITION COMMENTS AND DEFICIENCIES

I. Site Information

Figures 1.5, 1.6, 1.7, Well Completion Schematic

- Provide explanations for all acronyms used.

Response: Cabot has created an acronym list that includes explanations for all acronyms used on Figures 1.5, 1.6, and 1.7.

GLOSSARY AND DEFINITION OF ACRONYMS
For Figures 1-5, 1-6, 1-7

RKB	-	rotary kelly bushing
ppf	-	pounds per foot
DV tool	-	cementing stage tool
EUE	-	external upset ends – forging in ends on API pipe to provide additional thickness for strengthening connections
TAM	-	TAM International (oilfield services company)
RTS	-	radioactive tracer survey
H-40	-	API pipe grade
J-55	-	API pipe grade
K-55	-	API pipe grade
ST&C	-	short thread & coupled
LT&C	-	Long thread & coupled
sx	-	sacks
ID	-	inside diameter
PBR	-	polished bore receptacle
EPSEAL	-	epoxy resin cement

See new page 1-38a

II. Geology

As this is a renewal petition, U.S. EPA is concerned with whether the understanding of the geology of the injection and confining zones has improved since the last petition. Section 2 would therefore be strengthened by incorporation of more recent references, two of which follow. Submit an update to Section 2, incorporating these references. A third useful reference, although not recent, is included.

- Kolata, D.R., 2005, Bedrock Geology of Illinois, Illinois State Geological Survey Illinois Map 14: 1:500,000.
- Nelson, W.J., 1995, Structural features in Illinois, Illinois State Geological Survey Bulletin 100, 144 p.
- Piskin and Bergstrom, 1975, Glacial drift in Illinois: thickness and character, Illinois State Geological Survey Circular 490:35.

Response: These references have been included in the text

See Replacement page 2-13, 2-14, 2-27, 2-28, 2-37, 2-45, 2-46, 2-47, 2-59

Section 2.1 Introduction

- Page 2-2, Why was 45 miles chosen as the radius for the area of interest?

Response: The text has been revised to explain the area of interest. The area of interest was defined as 45 miles in the original 1990 *Final Report on Supplemental Characterization for Cabot Tuscola WDW-1 & 2 No Migration Petition Demonstration* as prepared by Albert S. Nieto, Consultant. This current Cabot Petition Renewal for exemption from the Land Ban Restrictions maintained this 45 mile radius to be consistent with previous documents.

See Replacement page 2-2

Section 2.2 Regional Geology

- Page 2-5, The Stratigraphic Column (Fig 2-1) should include the deeper formations discussed at the top of this page.

Response: The Stratigraphic Column (Figure 2-1) was revised to include the older (deeper) formations discussed.

See Replacement Figure 2-1

- Page 2-10, What hydraulic conductivity or other data are available to support the contention that the interbedded sandstones will dissipate pressure?

Response: The text has been revised to support the contention that the interbedded sandstones will dissipate pressure. Specific hydraulic conductivity data to support the assertion that the sands behave as pressure relief dissipaters does not

exist. General accepted empirical data is that sands have higher permeability than shales or limestone which would provide pressure relief.

<u>See Replacement page 2-10</u>

- Page 2-13, Please revise "Pennsylvanian rocks form the bedrock surface in Illinois" to "Pennsylvanian rocks form the bedrock surface *for most of* Illinois". Also, please provide a reference for drift thickness discussed on this page.

<u>Response:</u> The text has been revised as suggested regarding the bedrock surface. The drift thickness reference has been added to the text (Piskin, 1975).

<u>See Replacement page 2-13</u>

<u>Section 2.3 Local Geology</u>

- Page 2-28, Please clarify the "Cabot formations" discussed in the second paragraph.

<u>Response:</u> Cabot has revised the text to describe and clarify the "Cabot formations". These formations are the Franconia, Potosi, Eminence, and Oneota Formations of the Injection Zone, and the Shakopee Formation of the Confining Zone.

<u>See Replacement page 2-28</u>

- Page 2-29, The authors claim that "the waste injectate from the site will migrate to the northwest". This claim seems plausible but why wouldn't the waste also migrate to the ENE up the anticline (see Figure 2-14, 2-15 & 2-27)? It seems that numerical modeling is needed to evaluate waste migration possibilities. Does the USI injection well affect flow from the Cabot wells?

<u>Response:</u> Based on the limited structural data and mapping in the area, on the Potosi-Eminence formation, there exists potential for the waste to migrate to the northwest, but as the plume gets larger and spreads laterally, the structural high to the east-northeast may become prominent in trapping the waste fluid over 10,000-years. In either eventuality, Cabot has provided various models of the long-term waste drift plume cases in Section 3.0 Modeling. The long-term plume from Equistar tends to influence the Cabot waste plumes to orient more southeasterly due to the injected volume derived from Equistar displacing Cabot waste (see Figures 3-16 and 3-18).

- Page 2-29, In Section 2.3.2, oil and gas operations were described. Are they expected to affect lateral plume movement from the injection wells?

<u>Response:</u> Cabot has revised the text regarding the effects of oil and gas operations. The oil and gas operations within the local area (5 mile radius) will have no effect on the lateral plume movement from the injection wells since they are shallower than the

injection interval. The oil and gas operations to the northwest and southwest of the Cabot site are separated by a vertical thickness of greater than 2,000 feet of permeable and multiple impermeable sediments. There is no hydraulic communication between these producing intervals and the Cabot injection interval.

- Page 2-37, In the last paragraph, the authors refer to "Pennsylvanian bedrock valleys". The bedrock valleys have eroded the Pennsylvanian and older bedrock materials. Please revise.

Response: **Cabot has revised the text as suggested.**

See Replacement page 2-37

Section 2.4 Hydrogeology

- Page 2-45, Please expand on the shallow monitoring well program that was used to determine the direction of shallow groundwater flow. Please discuss the number of wells, well depth, dates, etc.

Response: **Cabot has included additional text describing the shallow monitoring program at the site. A copy of the shallow monitoring well program is included as Appendix 2-8, however this represents the historical monitoring program, which has evolved with some of the original monitor wells plugged. Presently the current program uses a limited number (6 site monitor wells) to monitor a horizon at 60-foot. The following text has been inserted and incorporated as part of the document.**

The shallow monitoring well program data is taken from: *Assessment of Fourth Quarterly (Annual 1991) Collected Groundwater Samples, Closed RCRA Impoundment, Cabot Corporation Plant, Tuscola, IL,* prepared by Hydropoll, Inc. in December 1991. A total of 25 wells are present on the plant grounds. Of this total, 19 are included in the monitoring system for the closed impoundment as approved by the Illinois Environmental Protection Agency. Nine wells are completed in the weathered till at depths of 20 to 30 feet, five wells are completed in a deeper sand unit in the till at approximately 100 feet, four wells are completed in the till at depths of 50 to 75 feet, and one deeper well drilled to a depth of 212 feet and screened in a silt from 199 to 203 feet. Four wells of the 19 total are located singly and 15 are located in multiple well clusters. One of the clusters is located upgradient and the remaining five clusters is located down gradient of the closed impoundment

Potentiometric maps were constructed from the water level data in the weathered till and in the deeper sand unit. The potentiometric surface map of the shallow groundwater showed the direction of the regional groundwater flow. The regional flow is to the southeast. A groundwater divide, across which no flow occurs, is located just north of the closed impoundment. The divide prevents flow of groundwater from the closed impoundment. The calculated field hydraulic conductivity in the shallow weathered till was 62,1 ft/year. Effective porosity of the

weathered till is estimated to be 0.10. A groundwater velocity of 4.0 ft/yr was calculated using these values.

Water levels in the deep sand did not vary significantly between the wells. A water level difference of only 0.57 feet was measured between the wells. The water flow direction within the deeper sand was tentatively determined to be to the west. Field hydraulic conductivity was determined as 3400 ft/yr. Effective porosity of the deep sand is estimated as 0.20. A groundwater velocity of 42.5 ft/yr was calculated using these values.

Water level differences in the well clusters indicated that the groundwater moves downward between the shallow till wells and the deep sand wells in the same cluster.

See Replacement Pages 2-vi, 2-45, 2-45a; new Appendix 2-8

- Page 2-46, The discussion of the Mahomet aquifer needs to be revised. My suggested rewrite for the first two sentences—

  The Banner Formation of east-central Illinois includes a thick, extensive sand member, the Mahomet Sand Member. This member is a valley train deposit which may be over 150 feet thick and is composed of clean sand, gravel, and minor amounts of silt and clay (Kempton et al., 1982).

Response: **Cabot has revised the text as suggested.**

See Replacement page 2-46

- Page 2-47, The authors should clearly discuss that Tuscola used bedrock wells for their water supply for over 50 years. These bedrock wells were completed in the Silurian dolomite. Details about Tuscola's water supply are available in Illinois State Water Survey Bulletin 40.

Response: **Cabot has added text to this section which details the use of the bedrock wells for the city of Tuscola's water supply. The city of Tuscola utilized wells completed in the Silurian dolomite for public water supply for over 50 years. These wells were typically openhole completions in the Niagaran Formation at depths below 400 feet. The well yields from these wells were generally less than 200 gallons per minute with varying water level drawdowns of 40 to 100 feet in specific wells (ISGS, 1950).**

See Replacement page 2-47

- Page 2-48, Please describe the technique used to estimate the hydraulic conductivity values discussed in the third paragraph.

__Response:__ **This text has an excerpt from the original 1990 Cabot Petition document. Specific documentation of the technique used to estimate the hydraulic conductivity values listed was not presented in the original document.**

- Page 2-49, Please clarify in which formation/aquifer you are describing the direction of groundwater flow.

__Response:__ **The text has been revised to clarify the aquifers for which the direction of groundwater flow is described. The groundwater flow within the Mocassin Springs Formation (lowermost USDW) is believed to be to the southwest due to the strutural and hydrologic influence of the high-relief Tuscola Anticline located to the northeast of the Cabot location.**

__See new Attachments 1 and 2__

- Page 2-51, In Sections 2.4.4 and 2.4.5, the authors use single data points to discuss the potentiometric surface. Please discuss the vertical and horizontal hydraulic gradients (assuming data are available to do so).

__Response:__ **Cabot contends that no specific data exists to calculate the vertical and horizontal hydraulic gradients because each of the pressure measurements was taken from a single point (depth) within the Well No. 3 wellbore.**

III. Flow and Containment Modeling

Section 3.2 Model Description

• Page 3-9, bottom paragraph; The description of the ideal plume is a valid tool for getting to the ideal form of a plume, but, in fact, besides complete homogeneity, the viscosity of the injected fluid needs to be relatively high and there must be a strong surface tension between very immiscible fluids to get that ideal cylinder.

Response: Per July 10, 2008 EPA meeting, no response required.

• Page 3-14, second paragraph; The vertical permeation model must take diffusive movement into account as well as pressure drive effects.

Response: The vertical permeation model does take both diffusive movement and pressure drive effects into account with the calculation performed in two parts. For the operational and future operational period, the DuPont Multi-Layer Vertical Permeation Model is used to determine the vertical movement due to pressure drive effects. The assumptions used in the model are described in detail in Appendix 3-4. The DuPont Molecular Diffusion Model is used separately to determine the vertical movement due to diffusion. The assumptions used are described in detail in Appendix 3-5. A sample calculation is also provided on page 3-27.

Section 3.7.5.3, Vertical Extent at 2057, states the most conservative determination of the maximum vertical permeation due to pressure effects at the Cabot site is 1.224 feet. As described in Section 3.8.2 Long-Term Vertical Extent, the most conservative determination of the maximum vertical movement due to diffusion during the 10,000 year period is 55 feet. The vertical movement due to diffusion for each waste stream constituent is shown in Table 3-12. The total vertical permeation at the end of the 10,000 year period would be the sum of the movement due to pressure effects plus diffusion (1.224 feet + 55 feet = 56.224 feet).

• Page 3-17, second paragraph; How is the geometric correction factor designed to be pessimistic?

Response: A detailed description of the geometric correction factor, G, is provided in Appendix 3-5 DuPont Molecular Diffusion Model, beginning on page 3-6. Tortuosity of the pore channels lengthens the total path over which molecules must travel. As a result, the diffusion coefficient of a solute species within a water saturated porous medium is always lower than in free water solution. In general it is found that the influence of the microgeometry can be characterized in terms of a "geometric correction factor" G. G is equal to the ratio of the effective diffusion coefficient in the matrix, D*, to the diffusion coefficient in the free solution D_o .

The pessimistic, or conservative nature of G is determined by a number of margins of safety that are inherent in the molecular diffusion model and in the recommended

procedure for determination of the key input parameter, the effective diffusion coefficient D*. This is summarized as follows:

- **Concentration at z=0 assumed equal to the waste concentration for all times.**
- **Chemical interactions with the aquitard are neglected, such as adsorption, ion exchange, molecular hindrance, and osmosic membrane effects.**
- **Horizontal movement of waste is neglected.**
- **Waste assumed to be no more dense than formation brine.**
- **Effective diffusion coefficient is determined conservatively.**
- **Chemical destruction of contaminants is neglected.**

Additional detail is provide in Appendix 3-5, Section V. Margins of Safety (page 24).

See Replacement page 3-17

• Page 3-18, third paragraph; Despite the fact that the distance of movement due to diffusion is relatively small, it should be included in calculations.

Response: Molecular diffusion is included in the vertical plume movement calculations, as described in Section 3, Flow and Containment Modeling of the 2007 Petition Renewal Document, and in the previous response.

The DuPont 10,000 Year Plume Model computer simulation software considers the effect of dispersion and density driven lateral plume movement. The effect of diffusion on lateral plume movement is considered in a separate calculation as described in Appendix 3-5 DuPont Molecular Diffusion Model. Table 3-12 shows the results of the calculation. Since lateral plume movement is through the injection interval which is predominantly dolomite, the values determined for a lithology of dolomite apply. Table 3-12 shows that the 10,000 year maximum lateral movement due to molecular diffusion is 15 feet for the waste constituent cyanide.

Section 3.5 Characteristics of the Injection Reservoir

• Page 3-26, top of third paragraph; When a feature is invoked, a reference which will allow the reviewer to confirm the claim should be listed.

Response: The first sentence of the third paragraph on Page 3-26 states that "Analysis of electric well logs from the injection wells, and distant offset penetration wells, allow the construction of subsurface geologic cross sections that indicate that the proposed injection and confining dolomite and shale layers are continuous and generally uniform in thickness". A sentence has been added to the page and states: "This is shown in the Geology Section, Figure 2-3."

See Replacement page 3-26

• Page 3-34 and Figures 3-13 thru 3-14; The figures indicate a very poor calibration. They do indicate that the model yields higher injection pressures than have been measured. Please revise.

<u>Response:</u> The objective of the model calibration effort is to demonstrate that the model prediction is conservative, not to match the observed pressures exactly. A conservative model approach was employed to over-estimate pressures. Based on a permeability of 3.6 darcies, and an interval thickness of 280 feet, the model predicts a pressure increase of approximately 10-15 psi. The measured annual well recorded pressure data indicates that injection interval pressure has decreased by 10-15 psi. This is unlikely, and is probably due to the initial pressure measurement being too high due to the inaccuracies inherent in the measurement of static reservoir pressures. This variability in pressures can occur due to gauge measurement error, directly from variation in shut-in times, or changes in injection rates from survey to survey. In any event, it is impossible for the model to show a decrease in pressure with injection, since this violates the principles of Darcy's Law for fluid flow in porous media.

Appendix 3-7 indicates that a calibration run sensitivity case (Run 2) was performed to predict the pressure increase using the 1990 Cabot Petition original model inputs of 446 feet thickness and 3.6 darcies permeability. This sensitivity case resulted in a predicted pressure buildup that was less than the base case, and is therefore considered less conservative and not appropriate.

• Page 3-34, top of last paragraph; Please illustrate how permeabilities are derived from log readings. Why were not the limestone porosities converted to dolomite porosities before whatever calculations were used were made?

<u>Response:</u> Permeability is not directly measured from open hole logs. However, an estimation of permeability can be calculated from other log derived parameters such as porosity and residual water saturation, and this is commonly done in computer analyzed logs. These estimates are commonly thought of as an "order of magnitude" permeability estimate. A commonly used correlation by Dresser-Atlas and others is the Timur Equation (Reference: Timur, A. An Investigation of Permeability, Porosity and Residual Water Saturation Relationships for Sandstone Reservoirs (Paper J). Transactions, SPWLA, June, 1968). Another commonly used correlation by Dresser-Atlas Services and others is the Morris and Biggs Equation (Reference: Morris, R. L., and Biggs, W.P. Using Log-Derived Values of Water Saturation and Porosity (Paper X). Transactions, SPWLA, 1967).

The Dresser-Atlas processed log assumed a limestone matrix density in the preparation of the log. It is common logging industry practice to use a limestone matrix as a default when computing porosity from density/neutron logs since lithology is often unknown. As mentioned in this paragraph, the assumption of a limestone matrix is conservative since this results in a lower calculated porosity than that calculated directly using a dolomite matrix. Use of a lower value for porosity

would result in a larger value for lateral waste movement. Therefore, this approach is conservative, since the calculated permeability is a direct function of porosity, the calculated permeability would also be lower, which would result in greater values of lateral pressurization.

<u>See Cited Reference Appendix, Timur, 8-1, 8-2, Morris and Biggs 8-2.</u>

• Page 3-36, top of page; If the highest vertical permeability measured in the Potosi was 2.0 x 10^{-7} darcys, the permeability is very low without further reducing the permeability. Please provide a calculation to show the effect of reducing the permeability even further. Why not assume the vertical permeability to be zero?

<u>Response:</u> "The aquiclude (dolomite or shale) layer permeabilities used for the determination of lateral pressurization are 1.00 E-16 darcies (see Table 3-1) are very low compared to the core measured values and are essentially "zero" in the model. This input minimizes vertical flow, and maximizes horizontal flow, which remains conservative for the lateral injection interval pressurization predictions.

To be conservative for the determination of vertical permeation, Cabot used a value of 1.0E-7 darcies. This maximized the waste interval pressurization values, and movement in the vertical direction.

• Page 3-36, last paragraph in section 3.5.2.3; Please provide a citation for the literature referenced.

<u>Response:</u> This paragraph states: "The aquiclude (dolomite or shale) layer permeabilities (see Table 3-1) for the reservoir model were determined from the literature correlations." This sentence has been removed and replaced with the following statement:

"The aquiclude (dolomite or shale) layer permeabilities used for the reservoir model are 1.00E-16 darcies (see Table 3-1) which are very low, essentially zero, and are very conservative for the lateral pressurization predictions. With regard to the vertical permeation case, based on Injection Well No. 3, the highest value for the vertical brine core permeability is 7.07E-8 darcies. To be conservative for vertical permeation, Cabot used a value of 1.0E-7 darcies."

<u>See Replacement page 3-36</u>

• Page 3-37, top of the second paragraph; Please provide some support for the statement that results are not particularly sensitive to the values for dolomite layer porosities. Reading on, why is waste drift related to porosity? Drift is governed by the rates of regional flow and buoyant flow. How are these related to porosity (unless you begin with head difference and other basic reservoir properties instead of a previously calculated rate of regional flow)?

<u>**Response:**</u> **The lateral pressurization model is more sensitive to permeability than porosity. This is described in detail in Appendix 3-2, which provides a detailed description of the DuPont Multi-Layer Pressure Model. Appendix 3-4 Page 4 states that: " Porosity enters into the model only through the contribution of fluid compressibility to the overall layer storativities. Storativity is a reservoir parameter which expresses the combined effects of layer porosity and compressibility. The model results are quite insensitive to the layer storativities, and therefore, also to the porosity values used. Typically, a 10 percent change in porosity will result in less than a 0.5 percent change in the predicted pressure buildup.**

Appendix 3-6 (DuPont 10,000 Year Plume Model) Page 10 provides the analytical solution to the equations for flow for a circular waste plume with density effects. As can be seen by examining the equation, buoyant waste movement velocity is inversely proportional to porosity. Therefore, assuming that all other parameters in the equation remain unchanged, an increase in porosity will result in a decrease in buoyant waste movement velocity.

<u>See Replacement page 3-37</u>

- Page 3-38, first paragraph; ". . . since permeation is inversely proportional to the dolomite or shale porosity." Seems to conflict with the statement in the last sentence of the second paragraph which states, "Predictions of injection interval pressure build up and . . . lateral waste movement . . . are entirely independent of the values specified for shale layer porosities." Any material diverted from storage in the more porous dolomite layers will not contribute to pressure increase and lateral movement. Given the large surface areas involved and number of interbedded shale and dolomite layers, it would seem that the influence might be significant. Please provide an illustration using the base equations used by the DuPont models.

<u>**Response:**</u> **The conflicting statement in the last sentence of the second paragraph is not correct and has been removed.**

The equations used in the DuPont Multi-Layer Vertical Permeation Model are shown in Appendix 3-4, pages 15 through 23. This determines vertical waste movement due to pressure effects of the injected fluid. The determination of vertical movement due to diffusion is described in Appendix 3-5, DuPont Molecular Diffusion Model. A sample calculation is provided on pages 27-28 of the Appendix that illustrates the methodology used.

<u>See Replacement page 3-38</u>

- Page 3-39, first paragraph; Please provide the information cited. Unless in one of the background documents we have already assembled, the pages including the information cited must be provided as well as the proper citation.

<u>**Response:**</u> **The first paragraph of Page 3-39 states: "Sediment compressibility values for the various layers in the geological model were established on the basis of**

information presented in Freeze and Cherry (1979) and developed by Neuzil (1987). The compressibility of the dolomite layers was taken as 1.8 x 10^{-7} pounds per square inch (psi), while those for the shales were specified higher at 1.3 x 10^{-7} psi^{-1}. The dolomite compressibilities are consistent with values used in other published literature for Midcontinent formations".

This section has been modified and replaced with the following:

"A review of published literature values of sedimentary formation compressibility (α) indicated a range of 10^{-6} to 10^{-11} in units of m^2/N or Pa^{-1} , equivalent to 10^{-4} to 10^{-9} psi^{-1} (Freeze and Cherry, 1979; Neuzil, 1987, see Cited Reference Appendix for a copy of the pertinent pages). Yale, et al., 1993, developed correlations to calculate formation compressibility based on rock type, depth, reservoir pressure, and overburden gradient (see Cited Reference Appendix for a copy of the pertinent pages in Yale's paper). For this demonstration, the technique developed by Yale, et al. was used to determine a unique value of compressibility for each layer in the DuPont model. The value for the injection interval dolomite was determined to be 1.8 x 10^{-7} psi^{-1}; the value for the overlying shale arresting layer was determined to be 1.3 x 10^{-7} psi^{-1}. These values are all well within the range of the published literature values mentioned previously."

See Replacement page 3-39

See Cited Reference Appendix, Freeze and Cherry p 55; Neuzil p 1176, Yale p 436, p 438.

- Page 3-42, equation; Please provide a tabulation of the measurements with information about their origin. Do they cover the entire injection interval? If the injection interval is randomly divided, do the measurements for each division yield the same multiplier?

Response: **This equation describes one method of calculating the multiplying factor, M as a function of porosity and permeability values from core data. Since site specific core data was not available for the Potosi-Eminence Dolomite injection interval, this technique was not used at Cabot to determine M. The second paragraph from the bottom of page 3-42 states the following: "Applying the above formula to the results of permeability and porosity measurements from Cabot Injection Well No. 3, a multiplying factor M of 2.54 was obtained for the injection dolomite interval." This paragraph is incorrect and was revised in response to this comment.**

The value of M = 2.54 was obtained using an alternative technique based on Gaussian dispersion predictions. The determination of M via this method is described in detail on pages 3-43 and 3-44.

See Replacement page 3-42

• Page 3-43, end of first paragraph; The dispersivity values used in many other demonstrations range up to 600 feet. Please provide a sensitivity analysis demonstrating what effect increasing longitudinal dispersivity will have on plume spreading.

__Response:__ **Section 3.5.6.2 was modified to provide additional justification for the dispersivities used for the Cabot site.**

The value for dispersivity is site and lithology dependant and in general is a function of travel distance. Therefore, although a value of 600 feet may be appropriate for another site, but this value is not appropriate for the Cabot site. Site specific parameters that affect dispersivities are injected waste volume, injection interval thickness, porosity, background velocity, and buoyant movement which is a function of formation dip angle and density difference between injectate and formation fluid. The equations developed by Xu and Eckstein (1995) were used to calculate longitudinal dispersivity for the Cabot site. An upper-end value of 123 feet for longitudinal dispersivity was calculated for the 2027 year-end operational plume, and the value of 252 feet was calculated for the longitudinal dispersivity utilized in the 10,000 Year Waste Plume Model. Based on Walton (1985), a value of 25 feet was determined to be appropriate for transverse dispersivity input values for the DuPont 10,000 Year Waste Plume Model.

For the 10,000-year plume modeling, porosity, formation dip, and waste density changes and variations were run in Sensitivity Model Cases 1-4. Table 3-10 presents these model inputs while Table 3-11 presents results of this sensitivity modeling, and Figures 3-22 through 3-27 provide graphical plots of model results. Table 3-11 shows a summary of the 10,000-Year Plume Model Results, consisting of a base case and 4 sensitivity runs. The development of the sensitivity cases is described in detail in Section 3.8 Long-Term (10,000-Year) Waste Containment, addressing the possible geologic, and waste density cases suitable for modeling.

__See Replacement pages 3-43, 3-44, 3-45, 3-45a__

• Page 3-45, second to last paragraph; It would be more appropriate to obtain the average surface temperature from climatic information. The temperature log of Cabot Injection Well No. 3 which was shut in for months before injection began should also be more accurate than measurements made during drill stem tests. The temperature in the region should be between 50 and 5° F. Please confirm the average surface temperature.

__Response:__ **The DuPont Multi-layer Model consists of 26 layers representing a depth interval from 3371 feet to 5392 feet. The temperature profile used for this interval to determine fluid viscosity in the model is well established by original openhole logs and temperature logs in the area and is independent of the average surface temperature.**

• Page 3-46 top of the page; What is the basis for the estimation of the base of USDWs? Please reference the section where it was discussed.

<u>Response:</u> The base of the lowermost USDW was conservatively determined at the Cabot site to be situated within the Moccasin Springs Formation at a depth of 2,700 feet. Original openhole logs and total dissolved solids (TDS) measurements were used to make this determination. The details regarding the basis for this determination are described in 2.0 Geology, Section 2.4.3 Determination of the Lowermost USDW.

- Page 3-46, table; We learned from the second to last paragraph of the previous page that there were drill stem tests used to collect water samples during the drilling of Injection Well No. 1. Why are none listed?

<u>Response:</u> A review of Cabot files indicates that temperature and fluid samples were taken, but in Injection Well No. 1 but no fluid sample TDS measurements were made.

- Page 3-47, third paragraph; How does this single pressure measurement yield a gradient of 0.435 psi/ft? Why is this measurement not included on Figure 3-12?

<u>Response:</u> Page 3-47 states that, "The first estimate of the original formation pressure for the injection dolomite was derived from an August 1, 1966, drill stem test measurement in Injection Well No. 1 (Cabot, 1966). The measured pressure was 1,915 pounds per square inch gauge (psig) at a depth of 4,580 feet BGL (temperature 109˚ F), which is a gradient of 0.435 psi/ft (see Figure 3-12). The pressure was corrected to the top of the injection interval (5,003 feet below ground level-BGL), using the above gradient."

This initial wellbore fluid gradient of 0.435 psi/foot listed on Table 3-6 comes from the original 1990 Cabot Petition page 10-9. Since this is almost identical to a fresh water gradient (0.433 psi/ft) it is likely that fresh water was in the hole at the time the static gradient pressure survey was taken, although it cannot be confirmed from records. The table of recorded drill stem test measurements below, yields a gradient of 1915 psig/4580 feet BGL = 0.418 psi/ft, which is not considered accurate as compared to the annual static formation testing performed on the wells with better gauges.

Depth	Pressure psig	Gradient
0	0	
1500	585	0.3900
3000	1230	0.4100
3580	1484	0.4145
4080	1701	0.4169
4580	1915	0.4181
4861	2035	0.4186

- Page 3-47, last paragraph; Why isn't the pressure measurement described here included in Table 3-6? This paragraph speaks of one footage depth and two pressures and "this gradient . . ." How was a gradient calculated from this information? Please include all information necessary to reach the results.

<u>Response:</u> This paragraph states that "In Cabot Injection Well No. 2, an Otis bottomhole pressure gauge was lowered to 5,200 feet into the freshwater filled wellbore on January 12, 1976, and recorded a pressure of 2,189 psig with a maximum recorded temperature of 112˚ F. The pressure recorded at the Eminence formation gradient stop was 2,102 psig. This gradient of 0.435 psi/ft reflects the freshwater in the wellbore. A follow-up bottomhole pressure gauge was lowered into Well No. 2 to a depth of 5,000 feet and a pressure of 2,096 psi was recorded (see Table 3-6)."

This pressure measurement is recorded on Table 3-6. Table 3-6 lists the pressure as pounds per square inch absolute (psia) which includes atmospheric pressure. Pressure recorded as pounds per square inch gauge (psig) can be converted to psia by adding the atmospheric pressure, 14.7 psi. In Table 3-6 this pressure is recorded as 2117 psia (2102 psig + 14.7 psi = 2117 psia). The follow-up pressure gauge recorded 2096 psig, which is listed in Table 3-6 as 2111 psia (2096 psig + 14.7 psi = 2111 psia).

The wellbore fluid gradient of 0.435 psi/foot listed on Table 3-6 comes from the original 1990 petition page 10-9. Since this is almost identical to a fresh water gradient (0.433 psi/ft) it is likely that fresh water was in the hole at the time the static gradient pressure survey was done.

- Page 3-48, third paragraph, How is the gradient indicated by a pressure measurement of 2035 psi at 4861 feet 0.432 psi/ft? Here 5003 feet is said to be the mid point depth. On the previous page, it was the depth to the top of the injection interval. Please correct this.

<u>Response:</u> This paragraph states that "An initial bottom hole pressure of 2,035 psig was measured at a depth of 4,861 feet in 1966, during testing of Cabot Injection Well No. 1. This corresponds to an average pressure gradient from surface to 4,861 feet of 0.432 psi/foot. Subsequent testing and model calculations utilize a midpoint depth datum of 5,003 feet for the Potosi-Eminence Dolomite Injection Interval."

The gradient listed here is a pressure vs. depth gradient, not a fluid gradient, and was calculated as follows: 2035 psig / 4861 feet = 0.4186 psi/foot.

<u>See Replacement page 3-48</u>

- Page 3-49, first paragraph; This paragraph says that the pressure gradient indicated by a pressure measurement of 2035 psi at a depth of 4861 feet is 0.4181 psi/ft. That is mathematically correct, and this tells us that the reservoir pressure won't support a column of fresh water to the surface. Other than that, the value has little application. Was this pressure measured or is it an estimate?

<u>Response:</u> This paragraph states that "Figure 3-12 is a graph of compiled well and formation pressures measured from historical pressure tests and also includes a graph of these pressure gradients plotted versus depth. It can be seen that slightly

different slopes are apparent within the scatter trend of the distributed data. The data corresponds with the overlying formation units and the Potosi-Eminence Dolomite Injection Interval. From these relationships, a detailed evaluation of the data indicates that the estimated original formation pressure (pre-injection) of the Potosi-Eminence Injection Dolomite Interval used in the model should be approximately 2,035 psi at a depth of 4,861 feet BGL, which is equal to a gradient of 0.4181 psi/ft. This formation pressure is supported by the data and derived from the calibration of the pressure model with the recent pressure measurements in Injection Well Nos. 2 and 3. This represents a conservative and reasonable value based on site-specific Cabot Plant data which has been plotted (Figures 3-13 through 3-15) and evaluated for its integrity."

This is a sub-hydrostatic gradient typical of older mid continent formations. It is based on site-specific historical formation pressure measurements vs. depth using a DST measurement and confirmed by pressure model results.

<u>Section 3.6 Model Calibration</u>

• Page 3-54, bottom paragraph; The pressure records indicate that there is direct pressure communication between the wells. However, the pressure changes measured in one well are not equal to the pressure changes measured in the other well. Therefore, the wells are not in direct hydraulic communication. That is, there is intact formation separating the caverns at the bottoms of the two wells.

<u>Response:</u> This paragraph states that "In 2006, an interference test was performed with Injection Well No. 3 and recorded a pressure increase of 0.65 psi at Injection Well No. 3 with a final pressure of 2,104.77 pounds per square inch absolute (psia) (datum of 5,005 feet). Within Injection Well No. 2, the final recorded pressure was 2,104.13 psia, representing a gain of only 0.09 psi over the recorded static pressure. This proves the wells and intervals are in direct communication."

<u>Response:</u> The wells are in direct hydraulic communication, since the pressure pulse caused by injection into Well No. 3 was observed in Well No. 2. If the wells were not in hydraulic communication, injection into Well No. 3 would cause zero pressure response in Well No. 2. The presence of more accurate and higher resolution gauges in later testing years have proven direct communication with a low response but direct effect of interference.

• Page 3-55, second paragraph; The injection of 250 gallons per minute (gpm) at the Equistar well seems to have an inordinate effect at the Cabot site. The pressure mound at Equistar is about equivalent to the pressure mound at the Cabot site where 400 gpm are injected. The 2006 interference test resulted in a pressure increase at the inactive well of just 0.09 psi at the inactive well. The injection rate is not provided, but it seems obvious that the injection activity at Equistar is going to have very little effect at the Cabot site. The statement that permeability has to be increased to result in a greater over prediction of pressure may be true if the desire is to increase the effect of injection at the Equistar site.

However, it would seem that the reverse is true if the effect of injection at the Cabot site is to be maximized. Please clarify.

Response: **Cabot re-ran the model (revising the model volume inputs for Equistar) and provided the results with replacements of Pages, Tables, Figures, and Appendix (CD-ROM). (see later NOD response beginning with Section 3.7 Model Predictions….Figure 3-16)**

The injection interval is modeled as a system, which incorporates injection at both the Cabot and Equistar sites, Ignoring injection at Equistar would reduce modeled pressure and would not be representative of the injection horizons, making the model output less conservative. Figure 3-19 is a pressure isopleth contour map that shows the model predicted pressure increase due to injection at year end 2027. The 400 gpm into the Cabot site is split between Well Nos. 2 and Well No. 3 with injection at 200 gpm per well. Injection into the Equistar well at 250 gpm is represented by the AP#3 location. The areal extent of the pressure mound at the Equistar well is less than at the Cabot site, which is reasonable since the total injection rate is less. The splitting of the Cabot total injection rate of 400 gpm into 2 wells results in a per well rate of 200 gpm, which is less than the modeled Equistar rate of 250 gpm down one well. The result of this scenario is to reduce the pressure peak at the Cabot location, since pressure increase at each well location is a direct function of the individual well injection rate. The model predicts that the pressure increase at Well No. 2 is 18.9 psi, at Well No. 3 is 18.8 psi, and at the Equistar well the pressure increase is 19.1 psi. The higher pressure increase at the Equistar well is reasonable, since the injection rate here is 250 gpm as compared to the 200 gpm per well rate for the Cabot injection wells.

Since the actual measured pressure increase due to injection during the 2006 interference test was only 0.65 psi at the injector, this implies that the permeability value of 3.6 darcies used for the injection interval is low, and therefore very conservative, since a pressure increase of around 18-19 psi was predicted.

The statement that permeability has to be increased to result in a greater over prediction of pressure is not correct; this has been changed to say that permeability has to be lowered to result in a greater overprediction of pressure.

See Replacement page 3-55

• Page 3-56, second paragraph; The figures showing the relationship of predicted to measured pressures show that the model grossly over predicts pressure increases resulting from injection. The model can only be considered calibrated if the aim was to grossly over predict pressure increases. Sensitivity testing should be used to determine what the effects of this relatively great over prediction are.

Response: **The objective of the model calibration effort is to demonstrate that the model prediction is conservative, i.e. not to match the observed pressures. Based on a permeability of 3.6 darcies, and a thickness of 280 feet, the model predicts a pressure**

increase of approximately 10-15 psi. The measured pressure data indicates that injection interval pressure has decreased by 10-15 psi. This is unlikely, and is probably due to the initial pressure measurement being too high due to the inaccuracies inherent in the measurement of static reservoir pressure. This can occur due to gauge measurement error, variation in shut in times, or changes in injection rates from survey to survey. It is impossible for the model to show a decrease in pressure with injection, since this violates the principles in Darcy's Law for fluid flow in porous media.

All of the subsequent pressures fall below the original model predicted values and at this permeability will still overmatch the pressure data. Appendix 3-7 indicates that a calibration run sensitivity case (Run 2) was performed to predict the pressure increase with the 1990 original petition model inputs of 446 ft thickness and 3.6 darcies permeability. This sensitivity case resulted in a predicted pressure buildup less than the base case, and is therefore less conservative.

- Page 3-56, table; What do these data represent? What is their significance?

<u>Response:</u> This paragraph states: "Various samples were taken, with final TDS measured at the end of sampling consisting of 18,720 ppm with a pH of 5.75 suggesting that the leading edge of waste plume spent-acid and waste reaction products are present in these samples."

Swabbed fluid (bbls)	TDS (ppm)
+ 1626 (1626 bbls total)	18,900 (conductivity method)
	24,856 (residual solids method)
+ 274 (1900 bbls total)	18,720

This allows judgement to be made on contamination of fluid or formation brine-plume fluid mixing. Generally the last sample set should be the cleanest and most valid.

- Page 3-57, second paragraph; The conclusion of the first sentence is in no way proven by the opening statement that heterogeneity is pronounced in the injection formations.

<u>Response:</u> The first sentence states: 'Since the Potosi-Eminence Injection Interval is represented by virgin native high permeability intervals, with cavernous and vuggy sections, as observed from drilling, the wells are proven to be directly connected (2006 Cabot Interference or pulse test, between Injection Well No. 2 and No. 3, yielded 0.65 psi increase)."

This sentence has been modified as follows:

The Potosi-Eminence Injection Interval is represented by virgin native high permeability intervals, with cavernous and vuggy sections, as observed from drilling. The wells are in hydraulic communication, as demonstrated by the results of the 2006 Cabot Interference Test that indicated pressure communication between Well Nos. 2 and 3.

See Replacement page 3-57

It is unclear how the penetration of the edges of the plumes proves anything. The model didn't predict penetration at any particular point in the plume, and there is no way to tell where in the plume the penetration occurred.

Response: **The model correctly predicted that the recently drilled Well No. 3 would penetrate the plumes generated by Well Nos. 1 & 2, as confirmed by the temperature log run on Well No. 3. A model predicted non-encounter would indicate that the employed porosity-thickness input values are too large, since the modeled plume extent would be smaller than the actual plume. Therefore, it can be concluded that the employed porosity-thickness values are not too large.**

The penetration of the plume does not involve an assumption of homogeneity because all that is demonstrated is a chance encounter. Neither does the result tell us that dispersion needs to be accounted for.

Response: **Cabot modeled the lateral waste plume movement based on Gaussian dispersion predictions. This conservatively models heterogeneity and dispersion, as described in detail in response to the EPA comment below.**

There will be dispersion because permeability is very irregular. That qualitative observation is insufficient to base a multiplier value on. There must be some data on which the multiplier was based. That data and the relation of the multiplier to the data must be clarified.

Response: **The value of M = 2.54 was obtained using by using a technique based on field-scale Gaussian dispersion predictions. The determination of M is described in detail in pages 3-43 and 3-44. The multiplier M is a function of the nominal plume radius (5252 feet, based on the injection volume, net thickness of 280 feet, and porosity of 4%), the concentration reduction factor (1 x 10^{-6}), and the dispersivity (123 feet, based on the equations developed by Xu and Eckstein, see page 3-46 of the revised modeling section). Since Gaussian dispersion predictions are expected to provide upper bounds to the advective dispersion present in the region near the source (Walton, 1985; Molz et al., 1983), the calculation of waste plume growth using a multiplying factor of M = 2.54 is very conservative.**

Section 3.7 Model Predictions

- Figure 3-16; The large size of the Equistar plume in relation to the Cabot plumes indicates the lack of a realistic result of the modeling. The actual volume injected to date should be easily available from the Illinois EPA and should have been used rather than the 250 gpm maximum allowable rate. The AOR radii are not marked on the figures.

<u>Response:</u> Cabot requested that the Illinois EPA (IEPA) provide all the injection volume data for the Equistar Well. This was done via a Freedom of Information Act (FOIA) request. IEPA only provided some of the data in paper form, as well as data on a CD-ROM which consisted of multiple pdf files that were copies of submittals made by the operator. Although injection into the Equistar well began in the latter part of 1970, the IEPA data only goes back to 1992.

At year end 2006 (12/31/2006), IEPA data indicated that 14.228532 billion gallons was injected into the Equistar Well. This is unlikely, since assuming that the well injected at 250 gpm throughout its entire history to 12/31/2006, this results in a volume of only 4.777470 billion gallons, which was the historical volume Cabot used in the Petition Reissuance submittal for the Equistar Well. After examining the data, it is Cabot's opinion that Equistar had made a +12.0 billion gallon error in reporting the cumulative injected volume in October of 1999. At the end of September of 1999, Equistar reported a cumulative injected volume of 1.374440 billion gallons. In October of 1999, Equistar reported a previous cumulative injected volume of 13.374440 billion gallons, an increase of 12.0 billion gallons.

Correcting the Equistar reported cumulative volume results in a cumulative injected volume of 2.228532 billion gallons as of 12/31/2006. The average rate over the approximately 36 year injection history for this well beginning in late 1970, is 114.1 gpm. This appears to be reasonable considering that the maximum permitted rate for this well is 250 gpm.

The model calibration cases and the model pressure and plume cases were rerun to reflect the actual Equistar historical injection volumes as determined above. These new results are shown in the revised model calibration Figures 3-13, 3-14, 3-15, revised pressure and plume plots Figures 3-17 through 3-19, revised upward permeation Figure 3-20, and revised model predicted presure increase at the injection wells, Figure 3-21. Tables 3-4 and 3-9 were also revised as result of the new model runs.

Per EPA's request, the 2.0 mile AOR was also drawn on the plume plots.

<u>See Replacement Pages 3-59, 3-60, 3-61, 3-62, 3-63, 3-64, 3-67</u>
<u>See Replacement Figures 3-13, 3-14, 3-15, 3-17, 3-18, 3-19, 3-20, 3-21;</u>
<u>See Replacement Tables 3-4, and 3-9.</u>
<u>See new Appendix 3-12 CD-Rom of Model Runs</u>

- Page 3-61, first complete paragraph; The pressure effect of the Equistar well should not be greater than the pressure effect of the Cabot wells.

<u>Response:</u> Based on the modeled injection rates, the pressure increase at the Equistar well should be greater than the pressure increase at the Cabot Wells. At

year-end 2006, the modeled injection rate into the Equistar well was 250 gpm. At year-end 2006, the modeled average historical injection rate into the Cabot Well No.1 was 0 gpm; 75.4 gpm into Cabot Well No. 2, and 96.2 gpm into Cabot Well No. 3. Even using the actual Equistar rate of 114.1 gpm, a higher pressure results. Since predicted pressure increase is a direct function of injection rate at each well, the model predicted results are entirely reasonable.

- Page 3-61, second complete paragraph; The first sentence states that the pressure build up, at the present, is due to a 400 gpm injection rate at the Cabot wells. This cannot be accurate because the Equistar well injecting at 250 gpm has a greater pressure effect.

Response: **The sentence that says the Cabot wells injected at 400 gpm is not correct (see response to the previous comment). This sentence was replaced with the following: "For the Cabot wells, the maximum pressure increase at year-end 2006 occurs at the Injection Well No. 3 and was calculated to be 11.08 psi."**

See Replacement Page 3-61

Section 3.8 Long-term Waste Containment

- Page 3-69, bottom; How was the direction of regional fluid movement determined? The text says that this velocity is consistent with the findings of several studies. Did these studies include the Illinois Basin? What do studies which focused on the Illinois Basin conclude? What is meant by "the sweeping action of the formation fluid?" What happens to constituents which are swept away? There must be some alteration of the plume configuration if there is such an effect. How was the work of the cited authors factored into the prediction?

Response: **The natural regional background drift velocity was estimated to be a maximum of 0.33 ft/yr in the downdip direction. Illinois Basin studies focus on regional shallow groundwater flow which is not applicable to the deep subsurface at 5000 feet where the Cabot waste is injected. The conservative assumption made in this study that the direction of regional groundwater movement is downdip relative to the Potosi-Eminence top of structure.**

This assumption is conservative for a waste which is more dense than the formation dip, since it maximizes waste movement (see results for Sensitivity Case 4, Figure 3-26). For the buoyant waste cases (Base Case, Sensitivity Cases 1 & 2), since buoyancy causes the plume to move updip, it is more conservative to assume that there is no natural regional background drift velocity, since this results in maximum waste movement.

The sweeping action of the formation fluid results in a closer grouping of the concentration contours at the leading edge of the plume. The constituents are not swept away from the plume entirely. They are redistributed along the length of the plume which causes the elongated teardrop shape with a sharp frontal edge.

The work of cited authors demonstrate that the value of 0.33 ft/year used in this study is appropriate. Clark (1988), concludes in his study that published literature and research show that deep saline aquifers have natural groundwater flow rates that are on the order of inches per year compared to the shallow freshwater aquifers which are often measured in feet per year. Bethke (1988), states that "Sediments generally accumulate in basins at fractions of millimeters per year, and fluids may move only in centimeters per year"

• Page 3-70, second paragraph; How are the effects of dispersion added to these distances?

<u>**Response:**</u> **The effect of dispersion is included in the DuPont 10,000 year model by inputting a value of 252 feet for horizontal dispersivity and 25 feet for transverse dispersivity. This paragraph was revised to state the following:**

"Density-driven drift is predicted to be a major factor in contributing to the long-term horizontal movement of waste at Cabot. The waste will travel in the long-term period as the average of the historical injectate density. The minimum modeled waste exhibits a lower density (0.990 g/cc) (buoyant-case) than the native formation fluid (1.02 g/cc) and will therefore tend to drift in the updip direction. Neglecting dispersion, the waste velocity due to buoyancy differences is approximately 4.4 ft/yr in the updip direction. Hydrodynamic dispersion will act to reduce the density-driven contribution to the overall velocities in the 10,000-Year Waste Plume Model. Considering dispersion, the Potosi-Eminence Dolomite waste plume would travel approximately 40,000 feet (7.57 miles)."

<u>See Replacement Page 3-70</u>

• Page 3-71, second paragraph; The range of concentrations, hazardous concentration threshold, and reduction factors to bring the maximum measured concentrations to the hazardous limits should be tabulated here or such a table should be referenced.

<u>**Response:**</u> **The calculated concentration reduction factors for the Cabot waste constituents is shown in Table 3-7. This sentence has been added to the referenced paragraph.**

<u>See Replacement Page 3-71</u>

• Figure 3-22; How were these distances calculated? If empirical calculations were used, then the details should be provided here.

<u>**Response:**</u> **The numerical data used to create this plot was generated by the DuPont 10,000-Year Plume Model. Values of C/Co (concentration reduction factor) versus x, y distance in feet were output by the model, then input into the Surfer contouring package to create the plume plots (Figures 3-22 through 3-26).**

- Page 3-75, bottom paragraph; What are the boundary assumptions which result in the distances cited? For instance, what is the starting concentration? Does this remain constant? What are the geometric correction factors for the two lithologies?

Response: **The assumptions used for the distances cited due to the model predicted molecular diffusion distances are shown in Table 3-12. The assumed initial concentration for each constituent is 1.0. The description of the DuPont Molecular Diffusion Model is provided in detail in Section 3.2.4 DuPont Molecular Diffusion Model and Appendix 3-4. The geometric correction factor for shale is G = ϕ^2 , where ϕ is porosity expressed as a fraction. For dolomite, G = ϕ (see Appendix 3-5 page 29).**

What are the sources for the diffusion coefficients?

Response: **The diffusivity in free solution is found using well-established predictive methods documented in the open literature (e.g., Lerman, 1988; Treybal, 1955; Bird et al., 1960; De Kee and Laudie, 1973) for both electrolyte (ionic) and non-electrolyte solutions. This is stated in the third paragraph in Section 3.2.4, DuPont Molecular Diffusion Model.**

CABOT TUSCOLA, IL
EPA PETITION COMMENTS AND DEFICIENCIES

INDEX OF SECTIONS and TABS