producing from wells more than 10,000 feet below ground surface. No production was identified in the Site area from this formation. Based on more recent data analysis from nearby wells, the Prairie du Chien is estimated to be approximately 550 to 560 feet thick and estimated to occur at approximately 4,338 feet BGS, or 3,635 feet BMSL (further detailed in Section B.8.2.2.3).

B.8.1.3.3 Middle and Upper Ordovician Units (Injection Zone and Upper Confining Zone)

St. Peter Sandstone/Glenwood Formation

The St. Peter Sandstone occurs unconformably above the Prairie du Chien, and is present in northern portions of the Michigan Basin. The St. Peter is mapped as absent in southern Michigan.

St. Peter/Glenwood can be a prolific oil producer in isolated areas of Michigan as indicated by Nadon, et al. (2000), who indicates that the "St. Peter-Glenwood interval contains numerous carbonate units that provide the basis for both regional correlation and subdivision of the section into at least 20 high-frequency sequences...the facies distribution of this mixed clastic/carbonate system also documents significant changes of local and regional tectonics."

The Glenwood Shale is dolomitic and sandy shale that occurs in the northwestern portion of the Michigan Basin. It thins to the east and is a greenish-grey shale in central Michigan. It is persistent and mappable throughout the Basin but typically is no greater than 20 feet thick. WMU (1981) suggests that this unit may serve as a Confining Zone, as it is "thought to be a barrier to the movement of hydrocarbons from the Black River Group into the underlying Prairie du Chien and Cambrian units".

Black River/Trenton Groups

The Black River Formation is composed of thick, undifferentiated dense brown/grey micritic limestones with cherty intervals and an altered volcanic ash layer called the Black River Shale. This shale is a thick yet distinctive bed, of limited extent, occurring in southern Michigan. Near outcrop, the Black River Formation may produce water from solution joints/fractures, but is "quite impermeable except where it has been dolomitized" in areas away from subcrop (WMU, 1981). The Trenton Formation consists of several hundred feet of light brown to brown limestone. It is 200-450 feet thick across the Michigan Basin. WMU (1981) states that "although the Trenton limestones are relatively impermeable, the possible presence of fractures and dolomitized zones could preclude its use as confining layer". The principle porosity zones are in areas of dolomitization. The Black River Formation is estimated to be approximately 185 feet thick and the Trenton Formation is estimated to be approximately 300 feet thick at the Site area based on nearby well log data. Cohee (1945) indicates that the combined thickness of the Trenton-Black River is approximately 400-500 feet thick in southern Ottawa County.

Richmond Group/Utica Shale (Upper Confining Zone)

The Richmond Group unconformably overlies the Trenton and Black River Formation. Regionally, it contains the Collingwood Shale and Utica Shale. The Collingwood can also be a shaley limestone but the formation is not reported to be present in southern portions of the State. The Trenton-Richmond Group (i.e., Utica Shale) stratigraphic boundary is "a widely recognized and traceable stratigraphic boundary throughout the basin, well-marked on both petrophysical and lithologic logs and also visible seismically. It is commonly used as a datum for structure contour maps and is assumed to be a chronostratigraphic surface" (WMU, 1981). Note that various authors disagree whether the Trenton-Utica contact is conformable.

The Utica Shale is upper Ordovician in age and records the influx of argillaceous mud into the depositional system. As a result, the Utica is a hard, dark gray to greenish black calcareous shale that is present throughout the Michigan Basin (WMU, 1981). Thickness varies from 150 to 400 feet thick (Figure B.8-16), and it is approximately 200 thick in the Site area. WMU (1981) states that "the very low permeability of this rather thick shale coupled with the fact that it forms the seal on known hydrocarbon traps indicates that it is an excellent confining layer". Figure B.8-17 is a structure contour map constructed at the top of the Utica Shale. The Utica Shale is the Upper Confining Zone.

At the top part of the Richmond Group is the Cincinnatian Formation. This formation consists of interbedded shales and carbonates. At the Site, the Cincinnatian is over 200 feet thick.

Clinton-Cataract Group

The Clinton-Cataract Group occurs atop the Richmond Group, and consists of the upper Cabot Head Shale and lower Manitoulin Dolomite. The Cabot Head is composed of shale. The Manitoulin is buff to light brown dolomite, locally cherty with interbedded shale or shaley dolomite (Ells, 1967). In the Site area, the Clinton-Cincinnatian sequence is approximately 90 feet thick based on nearby geologic data.

B.8.1.3.4 Silurian Units

Silurian units occur throughout Michigan and specifically in the Site area. The presence of low permeability units like shales and salts within the Silurian serve to impede vertical fluid movement.

Niagara

Matzkanin, et al. (1977) summarized the geology of the Niagara, stating "Niagara rocks in the subsurface are predominantly dolomites and limestones with scattered regional occurrences of cherty zones and thin shale beds. These rocks range in thickness from less than 100 feet in the basin interior to more than 1,000 feet at the basin margin…

pinnacle reef complexes [occur] a few miles basinward from the thick carbonate bank. Reefs, reef associated sediments, and biostromes occur at various stratigraphic levels within the Salina-Niagara Group."

WMU (1981) states that "in the subsurface of the Southern Peninsula of Michigan, rock of the Middle Silurian Niagara Group form gradation zones with distinctive rock characteristics. In the central part of the basin the Niagara Group consists of a thin (50-120 feet) dense limestone (micrite) termed the "basinal facies" that grades outward into a dolomitic limestone…then grades into a porous dolomite…termed the "shelf facies". The shelf facies…[that is] about 120 to 300 feet [thick]. The shelf facies is characterized by the presence of locally thick areas in the form of "pinnacle" reefs. Outwash this facies grades outward around the shelf facies into a thick (300 feet to 500 feet) zone…called the "bank facies". This zone is composed of porous and permeable dolomite and extends southward into Indiana and Ohio and northward into the outcrop area".

Data presented in WMU (1981) suggest that the Site area occurs along the transition of the shelf and basin facies of the Middle Silurian, where this author indicates that pinnacle reefs may develop. Log data suggest that the Niagaran is less than 60 feet thick in the Site area. The Niagara is a prolific oil and gas producer in Michigan, and data suggest that this was a primary oil and gas drilling target in portions of southern Michigan. Oil and gas fields are present in the region, some of which produce from various formations including the Niagaran/Salina. The Fillmore field occurs about 6 miles southwest of the Site and straddles the Ottawa-Allegan County line. This field produced from the Traverse and Salina A-1/A-2 carbonate. The field was discovered in 1940, with Salina production discovered in 1954. As of 1982, about 5,448,369 million cubic feet of gas had been produced from the Niagaran through 2010.

Salina Group

WMU (1981) states that the Salina Group is a "thick sequence of carbonate, anhydrite, silt and shale" that is restricted in areal extent to the approximate location of the Niagara Formation. The unit grades upward from the Basal "A" member (A-1 Evaporite, A-1 Carbonate, A-2 Evaporite and A-2 Carbonate) through F member, and is composed of interbedded shales, limestones and salts. The Salina-Bass Island group ranges in thickness from less than 100 feet to over 700 feet throughout the Michigan Basin. It should be noted that the Salina may contain several hundred feet of bedded salt, in total. Log data suggest that the Salina is approximately 750 feet thick in the Site area.

Bass Islands Group

The Bass Islands Group conformably overlies the Salina. The Bass Islands in the Michigan Basin generally consists of dense, buff dolomite and the upper part is sparsely oolitic. Lower in the section, gray argillaceous dolomites, shaley dolomites, and brown beds are present (Ells, 1967). WMU, (1981) states that the Bass Islands is described as a thick sequence of fine-grained dolomites that has floating anhydrite and celestite crystals, as well as some salt in central portions of the Michigan Basin. Regional data

suggest the Bass Islands Group ranges from 0-750 feet thick in the Basin center, and is about 75 feet thick in the Site area.

B.8.1.3.5 Devonian – Mississippian Units

Devonian-aged units present in the area include the Bois Blanc/Detroit River Group, Dundee Formation, Bell Shale, Traverse Group, Antrim, and Ellsworth Formations. Mississippian units include the Coldwater Shale and Marshall Sandstone. Devonian units are, in total, over 2000 feet thick in the Site area. The Devonian-Mississippian units are discussed individually, below.

Detroit River Group

WMU (1981) states that the Detroit River Group includes the Garden Island, Bois Blanc, Sylvania, Amherstburg, and Lucas Formations. The Detroit River Group is about 360 feet thick in the Site area. The Bois Blanc is composed of dolomite and cherty dolomites, with upper limestone-rich intervals. The Sylvania is sandstone, composed of well-rounded and sorted fine to medium grained quartzitic sandstone with thick chert and dolomitic intervals that is present in northwestern areas of the Basin. The Amherstburg is a dark brown to black carbonaceous limestone that is present in most of the Michigan Basin. It is poorly bedded and dense, and is not mapped by WMU (1981) as present in the Site area.

While the Detroit River includes the above formations, WMU (1981) indicates that it is "general practice" to only call that portion of the column between the top of the Amherstburg and Dundee the "Detroit River" and WMU (1981) states this portion of the column is sometimes referred to as the "Lucas Formation". This portion of the column includes the Richfield Member, which is a sequence of interbedded limestone, dolomite and anhydrite with minor amounts of sand, a massive anhydrite unit, and the Horner Evaporite composed of interbedded anhydrite, limestone, and salt. Wells in the vicinity of the Site found porosity and permeability development, but no commercial accumulations of hydrocarbons within the Detroit River Group.

Dundee Limestone

The Devonian age Dundee is predominately a carbonate section ranging from dense, fine-grained, light colored limestones on the east side of the state to coarse-textured bioclastic limestone (with portions secondarily dolomitized) in the central part of the state. In the Site area, the Dundee is about 120 feet thick. The Dundee is a prolific oil and gas producing formation in portions of the Michigan Basin. Recent examination of oil production in the Dundee and structural trends reveal a correlation attributed by some authors to hydrothermal dolomitization (e.g. Davies and Smith, 2006). The occurrence is attributed to movement of hydrothermal fluids along basement-rooted faults with subsequent dolomitization of carbonate sequences, primarily the Dundee. As shown in Figure B.8-3, none of these structural trends occurs in the Zeeland area.

Bell Shale

The Devonian age Bell Shale is typically soft, gray, gummy and silty shale containing scattered fossil fragments. The Bell Shale is not present in the Site area.

Traverse Group

The Traverse Group occurs above the Bell Shale (or the Dundee), and includes what is locally described as the Traverse Limestone and Traverse Formation. Both are described below. The Traverse Group is approximately 320 feet thick in the Site area.

Traverse Limestone. In western Michigan, the Devonian-age Traverse Limestone is dominantly a gray to gray-brown limestone, with lesser gray shales. A few anhydrite stringers may also be present. To the east, the Traverse Limestone becomes increasingly shaley, and in southeastern Michigan the unit is composed almost entirely of shale.

Traverse Formation. Below the Traverse Limestone is the Traverse Formation, and in the Warner-Lambert area this interval is composed of interbedded limestone and shale zone that is described as gray-tan and calcareous. This unit is described locally as interbedded tan-buff limestones that may be hard dense and fossiliferous.

The Traverse is an oil-producing formation in Kent, Ottawa, and Allegan counties. For example, the Salem field occurs southeast of Zeeland in T4N, R13W, and produces hydrocarbons from the Devonian Traverse limestone as well as the Detroit River Formation. Gas is also produced from the Silurian Salina A-2 carbonate. Checkley (1969) states that salt leaching is likely responsible for subsequent draping and fracturing of overlying units that created structures in which hydrocarbons accumulated.

Antrim Shale

The Antrim Shale conformably overlies the Traverse Group and has been subdivided by some authors into a lower "dark" Antrim and upper "light" Antrim, both of which consist of dark or light gray shales, respectively. Geophysical log signatures indicate that it has low permeability. The unit is estimated to be approximately 100 feet thick in the Site area.

Ellsworth Shale

The Ellsworth Shale conformably overlies the Antrim Shale and is composed of gray-green shale with minor amounts of sandstone and limestone. Geophysical log signatures indicate that it has very low permeability. The Ellsworth is approximately 560 feet thick in the Site area.

Coldwater Shale

The Coldwater Formation conformably overlies the Ellsworth Formation. It consists of grey shale. The Coldwater subcrops in the vicinity of the Site, and rapidly thins to zero to the southwest. At its thickest point, north of Saginaw Bay, the Coldwater is as thick as 1,300 feet (WMU, 1981). The unit is approximately 730 feet thick in the Site area based on well log data, where present. Figure B.8-18 is a regional isopach map of the Coldwater Shale.

Marshall Shales and Sandstones

The Marshall Shales/Sandstones occurs above the Coldwater shale, but presence and thickness in southwestern Michigan is highly variable due to erosion in some areas. As detailed in Section B.7, the Marshall Sandstone thickness ranges between 0 to 122 feet thick within an approximate one-mile radius of the Site boundary.

B.8.1.3.6 Glacial Drift

Figure B.8-19 is a generalized regional isopach of the Glacial Drift showing that the Drift is approximately 50 to 200 feet thick in the Ottawa County area. Sands are quartzitic and are medium to coarse grained in size, and clays are grey to light grey. As detailed in Section B.7 based on nearby data from drillers' logs, the thickness of the Glacial Drift ranges from 78 to 348 feet within an approximate one-mile radius of the Site boundary.

B.8.1.4 Regional Hydrology

WMU (1981) provided an evaluation of regional groundwater systems in Michigan, and assigned Ottawa and Allegan counties to the West Central Region 4 area (Figure B.8-20). According to this source, the primary regional sources of potable groundwater water are in the Glacial Drift, although some wells are completed in underlying Mississippian Shales and sandstones, including the Marshall Sandstone.

B.8.1.5 Regional Seismicity

The Autumn Hills RDF area is in a USGS designated minor seismic risk area (USGS, 2017). The site area has a peak acceleration of 4-6 percent g (Figure B.8-21), with a 2% probability of exceedance in 50 years. The University of Michigan (2015) indicated that the most recent earthquake with a magnitude greater than 4.5 occurred more than 60 years ago on August 9, 1947 near the town of Coldwater. It damaged chimneys and cracked plaster over a large area of south-central Michigan and affected a total area of about 50,000 square miles, including points north to Muskegon and Saginaw and parts of Illinois, Indiana, and Wisconsin. Since 2008, two earthquakes have been detected in southern Michigan, one northeast of Union City and another south of Galesburg.

B.8.2 Local Geologic Analysis

As shown on Figure B.4-1, summarized in Table B.4-1, and discussed in Section B.4, one well penetrates the upper confining zone (Utica Shale), but no wells penetrate to the Mt. Simon injection interval within a two-mile radius around the Autumn Hills RDF property boundary. The nearest wells penetrating to the Mt. Simon are two Class I Non-Hazardous Disposal wells at the Consumers Energy Zeeland Generating Station in Zeeland, Michigan (IW-1 and IW- 2, EPA Permit Nos. M-139-1I-004 and M-139-1I-005, respectively). These wells are both located in Section 17, T5N, R14W, and are located approximately 4.5 miles to the northwest of the Site.

Table B.8-1 below presents the formal well locations and names of nearby Mt. Simon injection wells, including the two nearest wells at the Consumers Energy Zeeland Generating Station, and nine additional nearby wells that penetrate to the Mt. Simon that occur in the Holland, Michigan area, approximately 10 to 11 miles west of the Autumn Hills RDF Site. Data from these 11 wells were used to assess the local geology and to define the characteristics of the Injection Zone and Confining Zones. When taken in conjunction with regional data, local well data show that the Injection Zone and Confining Zones are thick, laterally continuous, and well defined. A brief summary of the local stratigraphic column is presented below, followed by information pertaining to the physical characteristics of select units.

TABLE B.8-1. LOCATION OF NEARBY MT. SIMON DISPOSAL WELLS

Mt. Simon Well Location	Formal Well Name on Well Log	Well Name this Report
T5N R14W Sec 17	Mirant IW-1 (Consumers Energy)	Zeeland IW-1 (IW-1)
T5N R14W Sec 17	Mirant IW-2 (Consumers Energy)	Zeeland IW-2 (IW-2)
T5N R15W Sec 20	Park Davis and Company Mt. Simon #3	Pfizer No. 3 or Warner-Lambert Well No. 3
T5N R15W Sec 20	Parke Davis Mt. Simon No. 4	Pfizer No. 4 or Warner-Lambert Well No. 4
T5N R15W Sec 20	Pfizer Global Mf'g Mt. Simon #5	Pfizer No. 5 or Warner-Lambert Well No. 5
T5N R15W Sec 30	Heinz USA WDW No. 1	Heinz No. 1
T5N R15W Sec 30	Heinz USA WDW No. 2	Heinz No. 2
T5N R15W Sec 30	H.J. Heinz Company Heinz WDW #3	Heinz No. 3
T5N R15W Sec 30	Chemetron Corporation Deep Well No. 1	BASF No. 1
T5N R15W Sec 30	Chemetron Corporation Chemetron D-2	BASF No. 2
T5N R15W Sec 30	Chemetron Corporation D-3	BASF No. 3

Figure B.8-22 presents a regional SW-NE cross section that transects the site for the Mt. Simon portion of the geologic column through the Michigan Basin (Barnes et al. 2009). The location of a local cross section intersecting the Pfizer No. 5 and Mirant IW-1 injection wells is presented on Figure B.8-23 and the local west-east cross section showing the stratigraphic sequence near the site is shown on Figure B.8-24.

Local isopach and structure contour maps were generated for formations of interest in the Site area from available regional data. Maps were constructed based on a combination of well log picks and formation tops from the Michigan Department of Environmental Quality well database. Text discussion for units includes formation thickness and formation top information derived from wellsite geologist formation descriptions, but every value may not always directly correspond to the values presented on the associated structure contour and isopach maps. These small discrepancies are due to different methodologies for "picking" formations (i.e. during drilling vs. well logs). Significant differences between the data sources are identified and discussed in the text as appropriate, but minor variations of a few feet do not impact conclusions and are not explained further in subsequent sections of this document.

Estimated depths of deeper formations in the Site area are based on an evaluation of these local structural contour maps, as there is no well control in the immediate vicinity of the IW-1 well below the Black River Formation. The nearest wells that penetrate below this depth and to the Mt. Simon injection interval are the two wells at the Consumers Energy Generating Station in Zeeland, located approximately 4.5 miles northwest of the site.

B.8.2.1 Local Structural Geology

Regional structure contour maps are presented in Figures B.8-6, B.8-8, B.8-10, B.8-13, B.8-15, and B.8-17. Local structure contour maps were constructed based on these maps with refinement using additional well data available from the Consumers Energy Zeeland Generating Station and other nearby Mt. Simon disposal wells, as well as other well logs and the Michigan DEQ Formation Tops database. Local maps are presented as they are discussed in subsequent sections. These maps were generally constructed using 50 foot contour intervals or alternates as appropriate for clarity of presentation. Consistent with regional characterization discussed in Section B.8.1, the analyses and mapping indicate that there are no major or mappable structural features within the Site area. Site-specific data also indicate that there are no faults that transect the Injection Zone or Confining Zone locally. That is, the Injection Zone and Confining Zone are laterally continuous, with no abrupt changes in thickness or lithology within a 10-mile radius of the Site.

A local structure contour map was constructed at the top of the Mt. Simon using the gamma ray signature identified by Barnes et al. (2009) as the top of the Mt. Simon. Figure B.8-25 presents this surface. As shown in this figure, over the entire area the Mt. Simon dips approximately 60 feet per mile (less than 0.65 degrees) to the northeast. Local dip direction is approximately N 48° E and the direction appears to be consistent in local and regional analyses.

B.8.2.2 Local Stratigraphy

Table B.8-2 presents the estimated depths to formation tops. These depths are based on nearby oil and gas wells (with the deepest penetration extending to the Black River

Formation), as well as depths extrapolated from the local structural contour maps described in Section B.8.2, including the two Mt. Simon wells at the Consumers Energy Generating Station (see Figure B.4-1). Table B.8-3 presents the formation thicknesses that are estimated from these data.

TABLE B.8-2. ESTIMATED FORMATION TOPS AT THE PROPOSED AUTUMN HILLS IW-1 LOCATION

Formation	IW-1 Est. Depth to Top, from GL (ft)	IW-1 Est. Depth to Top, ft BSL
Ground Level (feet ASL)	703	-----
Glacial Drift	0	-703
Marshall Sandstone	160	-543
Coldwater Shale	220*	-483
Ellsworth Shale	950	247
Antrim Shale	1,510	807
Traverse Group	1,610	907
Dundee Limestone	1,930	1,227
Detroit River Group	2,050	1,347
Bass Island Group	2,410	1,707
Salina Group	2,485	1,782
Niagara Group	3,245	2,542
Clinton Group	3,295	2,592
Cabot Head Shale	3,345	2,642
Manitoulin Dolomite	3,365	2,662
Undifferentiated Upper Cincinnatian	3,385	2,682
Utica Shale	3,663	2,960
Trenton Formation	3,853	3,150
Black River Formation	4,153	3,450
Prairie du Chien Group	4,338	3,635
Trempealeau Formation	4,893	4,190
Franconia Formation	5,103	4,400
Dresbach Formation	5,228	4,525
Eau Claire Formation	5,373	4,670
Mt. Simon Sandstone	5,578	4,875
Precambrian Granite Wash	6,570	5,867
Precambrian basement	6,600	5,897

*Estimated depth to base of USDW at proposed well location; USDW is identified at 348 feet thick elsewhere in the Autumn Hills RDF boundary, so 350 feet is conservatively used in well designs and calculations.

TABLE B.8-3. ESTIMATED FORMATION THICKNESS AT THE PROPOSED AUTUMN HILLS IW-1 LOCATION

Formation	IW-1 Est. Thickness (ft)
Glacial Drift	160
Marshall Sandstone	60
Coldwater Shale	730
Ellsworth Shale	560
Antrim Shale	100
Traverse Group	320
Dundee Limestone	120
Detroit River Group	360
Bass Island Group	75
Salina Group	760
Niagara Group	50
Clinton Group	50
Cabot Head Shale	20
Manitoulin Dolomite	20
Undifferentiated Upper Cincinnatian	250
Utica Shale	190
Trenton Formation	300
Black River Formation	185
Prairie du Chien Group	555
Trempealeau Formation	210
Franconia Formation	125
Dresbach Formation	145
Eau Claire Formation	205
Mt. Simon Sandstone	992
Precambrian Granite Wash	30

The top of the Mt. Simon Sandstone is projected to be at about 4,875 feet below sea level (ft BSL), or 5,578 feet below ground level (ft BGL), based on a ground level elevation of 703 feet above mean sea level (ft AMSL). The Mt. Simon is approximately 1,000 feet thick at this location. The proposed Injection Zone for the Site wells consists of the Trenton/Black River, Prairie du Chien, Trempealeau, Franconia, Dresbach/Galesville, Eau Claire, and Mt. Simon Formations; the overlying Utica Shale is the Upper Confining Zone.

B.8.2.2.1 Precambrian

The Precambrian granite wash was encountered in both of the Consumers Energy Zeeland Generating Station (formerly Mirant) wells, located approximately 4.5 miles northwest of the Autumn Hills RDF. This unit is described as quartz, clastics, and mineral fragments that are generally angular to very angular, tabular, and platey. The wash is orange/red with dark green tints, with some recrystalized quartz grains that are

lighter/tan or cream in color. Chlorite, mica, black mineral fragments, and plagioclase fragments are present; it is described as having "no porosity". Due to limited well control in the area, a local structure contour map of the top of the Precambrian basement was not constructed, but appears to be approximately 6,600 feet BGL near the site.

B.8.2.2.2 Cambrian (Injection Zone)

Mt. Simon (Injection Interval)

The Mt. Simon is a thick and ubiquitous sandstone sequence that is present above the Precambrian in the Site area. Figure B.8-25 is a structure contour map constructed at the top of the Mt. Simon, and Figure B.8-26 is a local isopach map of the Mt. Simon. These maps show that the Mt. Simon is present throughout the area, and approximately 1,000 feet thick in the Site area. Observed thicknesses at the Consumers Energy Zeeland Generating Station wells, located northwest of the Site, are approximately 1,050 feet. At the more distant Warner-Lambert (Pfizer) site wells near Holland, 865-944 feet of Mt. Simon was penetrated in the three site wells, though none of the wells reached basement. At the BASF and Heinz sites in Holland, the Mt. Simon is approximately 831-893 feet thick.

Cores were taken from the Mt. Simon in the Warner-Lambert No. 5 well from 5,200-5,231 feet BGL and BASF Well No. 1 from 5,300-5,335 and 5,516-5,576 BGL that are located west of the Site area. Cuttings samples were also collected from two of the BASF wells, Heinz No. 2 and the Warner-Lambert wells. Descriptions of the cores and cuttings indicate that the cored Mt. Simon intervals are composed of sandstone that is gray, very fine-grained, with occasional shaley laminae. The sandstone is described as moderately indurated. The Warner-Lambert No. 5 core (as well as the other cores taken from this well) was also analyzed for porosity and permeability, and is presented in Tables B.8-4a and B.8-4b. Table B.8-4a summarizes porosity and permeability data for the cored intervals. Table B.8-4b presents depth and core specific permeability, porosity, and grain density values for core plugs within these intervals.

TABLE B.8-4a. MT. SIMON CORE DATA, WARNER-LAMBERT WELL NO. 5

		Permeability-Air (md)		Permeability-Fluid (md)	
Plug Interval (ft RKB)	Horizontal Plug Porosity	Ambient Horizontal	Net Overburden Horizontal	Brine Horizontal	Waste Horizontal
5,200-5,201	0.17	193.6	104.0	227.5	192.6
5,206-5,207	0.19	124.7	62.8	TBFA	TBFA
5,214-5,215	0.17	33.9	9.8	210.9	209.8
5,222-5,223	0.13	101.9	44.8	141.9	152.1
5,229-5,231	0.14	6.2	2.5	2.4	--------

*TBFA = too broken for analysis

TABLE B.8-4b. MT. SIMON CORE PLUG ANALYSES, WARNER-LAMBERT WELL NO. 5

			Horizontal Permeability (md)	
Plug Depth (ft RKB)	Grain Density (g/cm3)	Porosity	Air	Brine
5,200.5	2.615	0.17	193.6	277
5,206.9	2.613	0.19	124.7	TBFA*
5,214.3	2.608	0.17	33.9	211
5,221.1	2.637	0.16	101.9	141.9
5,229.2	2.612	0.13	6.2	2.4

*TBFA = too broken for analysis

Core data indicate that the porosity ranges from 13-19%, while horizontal brine permeability ranges from 2.4 to 277 md.

Fluid samples and test data were obtained during drilling from the IW-1 and IW-2 wells at the Consumers Energy Zeeland Generating Station site. Raw data is available in the completion reports for the wells submitted in 2001 (Resources Services, USA, 2002a and 2002b). Injection Zone fluids at these wells were determined to have a TDS of 190,000 to 222,000 mg/l. Original reservoir pressure at the IW-2 well was determined to be 2,429.5 psi at a depth of 5,280 feet RKB (5,267 feet BGL) in the Mt. Simon. This is equivalent to a gradient of approximately 0.46 psi/ft, and is consistent with expected Mt. Simon pressures in this part of Michigan. In addition to the above core analyses, samples from the BASF No. 3 well located in Section 30, T5N R15, were tested for Mt. Simon reservoir characteristics. Although limited information regarding test specifics are available, well records provide the following information pertaining to the test on this well (Table B.8-5). Original pressure data indicates a gradient of approximately 0.46 psi/ft, similar to the results from the Consumers Energy IW-2 well.

TABLE B.8-5. BASF NO. 3 IN-SITU MT. SIMON FORMATION TEST RESULTS

Well No.	Effective Porosity (%)	Effective Permeability (md)	Reservoir Pressure (Psig)	Reservoir Fluid Analysis (mg/l)	Receiving Formation	Injection Interval
BASF NO. 3	12.2	Dresbach: 440 Mt. Simon: 330	2,158-Original Pressure at 4,666'	Cl: 155,000 Mg: 3,900 Ca: 13,000 Na: 78,000 SG: 1.16 pH: 6.2	Mt. Simon Sandstone	4,745-5,550

Local Lithologic Analysis and Reservoir Characteristics

The Mt. Simon has recently been studied as a possible candidate formation for CO_2 injection and results of these analyses also provide information pertinent to fluid injection at the Site. Barnes et al. (2009) evaluated the sedimentary facies, lithology,

and petrophysics of the Mt. Simon in the Holland area to further understand porosity and permeability development. These authors recognized that the Mt. Simon can be subdivided into three general units: a basal pink-red hematite-stained arkosic unit, central medium-coarse grained quartz sandstone with minor shale/glauconite, and upper transitional calcareous, argillaceous sandstone with fine-grained arkose interbeds that occurs conformably below the Eau Claire. Figure B.8-27 presents these facies from the Mirant Zeeland (Consumers Energy Generating Station) IW-1 well showing the three general units as identified by Barnes et al. (2009).

Eau Claire Formation (Injection Zone)

Regionally, the Eau Claire is highly variable from a compositional standpoint, consisting of fine grained sandstone with dolomitic cement in its lower half and siltstones, shales, and sandstone in the upper half. The entire thickness is glauconitic. The Eau Claire thickens to over 800 feet toward the center of the Michigan Basin (Figure B.8-9).

The BASF Well No. 1, located more than 11 miles west of the site, was cored through the Eau Claire (Core No. 1). At this location, the Eau Claire is described as consisting entirely of sandstone that is white to light grey-green in color and fine to coarse-grained, with portions of the interval being friable. Additionally, the Eau Claire has occasional dark, argillaceous streaks, with “flat tabular black specks” in some locations. The core is described as being glauconitic throughout, with more glauconite at the bottom of the cored interval. Porosity is described as varying from 3-18%. The Warner-Lambert No. 5 well was cored through the Eau Claire from 4,912-4,941.3 ft. The core description states that this interval is composed of brown to brown-black sandstone that is fine to medium-grained with slightly calcitic cement and reddish brown lamina. The zone is described as being moderately indurated, and the interval has shaley laminae throughout with occasional black shale intervals. Specifically, the core was described by Terra Tek as "sandstone, brown to black, fine grained slightly calcareous cementing with reddish brown shale lamination." The description of the Eau Claire is fairly consistent throughout the length of the core. From the core description, it appears that the shale lamination increases toward the bottom of the core. Well log data suggest that the Eau Claire is about 191-195 feet thick at the Warner-Lambert wells. Five core plugs were taken from the Warner-Lambert No. 5 Eau Claire core. Also, a core flow study was conducted on the two cores taken from the Eau Claire, one upper and one lower, based on samples obtained during the drilling of the Warner-Lambert No. 5 well. Interval data and plug-specific information was obtained. These results are presented in Tables B.8-6a and B.8-6b, below.

TABLE B.8-6a. EAU CLAIRE CORE DATA, WARNER-LAMBERT WELL NO. 5

		Permeability-Air (md)		Permeability-Fluid (md)	
Plug Interval (ft RKB)	Horizontal Plug Porosity	Ambient Horizontal	Net Overburden Horizontal	Brine Horizontal	Waste Horizontal
4,912-4,913	0.11	0.744	0.365	2.142×10^{-4}	1.621×10^{-4}
4,918-4,919	0.14	6.747	6.342	2.23	---
4,926-4,927	0.17	1.483	0.968	1.366×10^{-4}	---
4,933-4,934	0.09	4.308	0.338	2.411×10^{-5}	---
4,940-4,941	0.15	1.059	0.324	1.83×10^{-4}	---

TABLE B.8-6b. EAU CLAIRE CORE PLUG ANALYSES, WARNER-LAMBERT WELL NO. 5

			Horizontal Permeability (md)		Vertical Permeability (md)	
Plug Depth (ft RKB)	Grain Density (g/cm3)	Porosity	Air	Brine	Brine	Injectate
4,912.5	2.689	0.11	0.744	2.14×10^{-4}	---	---
4,913.5	---	---	---	---	1.4×10^{-5}	1.7×10^{-5}
4,918.3	2.657	0.14	6.747	2.23	---	---
4,919.5	---	---	---	---	3.0×10^{-3}	4.0×10^{-3}
4,924.5	---	---	---	---	2.0×10^{-3}	3.0×10^{-3}
4,926.9	2.592	0.17	1.483	1.366×10^{-4}	---	---
4,930.5	---	---	---	---	$<10^{-6}$	5.2×10^{-6}
4,933.3	2.666	0.09	4.308	2.4×10^{-5}	---	---
4,936.5	---	---	---	---	1.4×10^{-6}	7.0×10^{-6}
4,940.7	2.647	0.15	1.059	1.83×10^{-4}	3.0×10^{-3}	2.0×10^{-3}

To summarize, all descriptions indicate that the Eau Claire Formation in the vicinity of the Site is composed of sandstones with interbedded shale. The unit is relatively porous, but exhibits low horizontal permeabilities of between 1.366×10^{-4} and 2.411×10^{-5} md. Vertical permeabilities to brine of between 5.2×10^{-6} and 4.0×10^{-3} md were measured. Geological literature regarding the Michigan Basin does not indicate the potential for fracturing or faulting of the Eau Claire. Detailed local correlations of the well logs available for wells in the area and structure mapping also show no evidence of faulting within the geologic column as a whole in the area and, specifically, the Eau Claire, indicating the suitability of the formation as an aquiclude or aquitard.

As shown on Figure B.8-28, the Eau Claire is approximately 200 to 220 feet thick in the Site area. Figure B.8-29 is a local structure contour map constructed at the top of the Eau Claire. The top of the Eau Claire is estimated to occur at approximately 4,670 ft BSL, or 5,373 ft BGL.

Galesville/Dresbach (Injection Zone)

The Galesville/Dresbach is locally described as a sandstone that is clear to frosted; it is very fine to coarse grained with moderate to well-sorted subangular to rounded grains and trace glauconite. The Dresbach was cored at Warner-Lambert No. 5, with the cored interval from 4,822 to 4,850.5 ft BGS (Table B.8-7a). The core description indicates that this interval is composed of sandstone that is gray to dark gray, fine grained, and massive, with moderate to poor induration and occasional shaley lamina, particularly near the base of the unit. It is also calcareous. Terra Tek described it as "sandstone, light grey to grey, very fine grained at the top of the core (4,822 feet to 4,828 feet) with laminations of heterogeneous cementing, friable, clasts". From 4,828 feet to 4,846 feet the core is described as "sandstone, grey to dark grey, fine grained, massive in some places with occasional shale lamination". From 4,846 feet to 4,850.5 feet the lithology changes slightly again to "sandstone, dark grey, fine grained with occasional shale laminations, slightly calcareous". Core was analyzed, and the results of this analyses as well as plug sampling results are presented in Tables B.8-7a and B.8-7b.

TABLE B.8-7a. DRESEBACH CORE DATA, WARNER-LAMBERT WELL NO. 5

		Permeability-Air (md)		Permeability-Fluid (md)	
Plug Interval (ft RKB)	Horizontal Plug Porosity	Ambient Horizontal	Net Overburden Horizontal	Brine Horizontal	Waste Horizontal
4,822-4,823	0.11	374.949	155.495	241.764	---
4,829-4,830	0.19	1,818.168	437.111	2,029.131	---
4,837-4,838	0.17	627.395	235.426	562.335	---
4,844-4,845	0.18	760.326	324.910	386.644	---
4,848-4,850.5	0.20	169.010	25.646	115.079	---

TABLE B.8-7b. DRESBACH CORE PLUG ANALYSES, WARNER-LAMBERT WELL NO. 5

			Horizontal Permeability (md)	
Plug Depth (ft RKB)	Grain Density (g/cm^3)	Porosity	Air	Brine
4,822.9	2.666	0.110	374.949	242
4,829.5	2.641	0.190	1,818.168	2,030
4,837.4	2.627	0.170	627.395	562
4,844.0	2.635	0.180	760.326	337
4,848.7	2.600	0.200	169.010	115

Figure B.8-30 is an isopach map of the Galesville/Dresbach, which shows that the interval is approximately 140 to 150 feet thick in the Site area. Figure B.8-31 is a structure contour map constructed at the top of this interval, indicating that the top of this formation is projected to occur at approximately 4,525 ft BSL, or 5,228 ft BGL.

Franconia (Injection Zone)

The Franconia is present in the Site area, and is described in areas west of the Site as a sandstone and dolomite unit, with sandstones that are fine to medium grained, light grey, with abundant glauconite and a trace of chert with some red staining. The dolomitic portion is described as being sandy. Figure B.8-32 is an isopach map of the Franconia, which shows that the interval is approximately 120-140 feet thick in the Site area. Figure B.8-33 is structure contour map constructed at the top of this interval, indicating that the top of the formation is projected to occur at approximately 4,400 ft BSL, or 5,103 ft BGL.

B.8.2.2.3 Ordovician (Injection Zone and Confining Zone)

In contrast to the deeper Cambrian units, units within the Ordovician are composed predominantly of carbonates, indicative of changes in the regional depositional systems. Ordovician units present at the Site are described below.

Trempealeau Formation (Injection Zone)

To the west of the Site, the Trempealeau is described as dolomite that is sandy at the base, with decreasing sand percentage up-section. The dolomites are light tan to tan and grey in color, with red/pink coloration and varying intercrystalline porosity. The units are variably described as fine to medium grained (sucrose to micritic), and may contain shale that is present in traces. Glauconite is also present. Figure B.8-34 is an isopach map of the Trempealeau, which shows that the interval is approximately 200 feet thick in the Site area. Figure B.8-35 is structure contour map constructed to the top of this interval, indicating that the top of the formation is projected to occur at approximately 4,190 ft BSL, or 4,893 ft BGL.

Prairie du Chien Group (Injection Zone)

The Prairie du Chien Group occurs above the Trempealeau, and is early Ordovician in age. The Prairie du Chien Group is a relatively thick interval of dolomites; chert-rich intervals are present throughout, and a sandstone interval is typically present in the upper portions of the Group. The dolomite is described as a light tan to light grey in color, and is finely sucrosic to finely crystalline with sand and occasional abundant drusy quartz and possible vug fillings. Shales are also present within the unit, including the Brazos shale. Lower portions are described as glauconitic or red in color.

The Prairie du Chien in the general area is composed of thick sequences of interbedded dolomites with shale and sand-rich layers. It is composed of two Formations, the Oneota and Shakopee, that include (according to Smith et al., 1993) the Willow River (sandy dolomite), New Richmond (silty-sandy dolomite), Hager City (dolomite) and Stockton Hill (sandy dolomite), based on outcrop differentiation. Close examination of the data suggest that the Group is composed of several different depositional sequences. The contacts between these layers are “sharp and also appear to be

disconformable" (Smith et al., 1993). As a result, the unit, while primarily composed of dolomites with shell interbeds, exhibits layering that will serve to define properties that would limit the potential for vertical fluid movement and transport. As indicated in the regional discussion, sandstones overlying the Prairie du Chien are sometimes included within the Prairie du Chien group. However, these intervals are addressed as part of the Glenwood Shale-St. Peter Sandstone discussion, presented below.

Figure B.8-36 is an isopach map of the Prairie du Chien Group, which shows that the interval is approximately 550-560 feet thick in the Site area. Figure B.8-37 is structure contour map constructed to the top of this interval, indicating that the top of the formation is projected to occur at approximately 3,635 ft BSL, or 4,338 ft BGL.

Glenwood Shale-St. Peter Sandstone Interval (Injection Zone)

Regionally, the Glenwood-St. Peter Sandstone interval occurs above the Prairie du Chien interval and is up to 100 ft thick in northern portions of Ottawa County, but locally the unit is thin and composed of shales, limestones and minimal sandstone. Data from the nearby Consumers Energy Generating Station wells support the regional analysis that suggest the St. Peter Sandstone is absent at the Site location.

Black River Formation - Trenton Formation (Injection Zone)

The Black River Formation is ubiquitous in the Site area. It is composed of limestone that is described as light tan to grey and buff in color, and finely crystalline to chalky to micritic, with a few imbedded dolomite rhombs. Occasional shale intervals are described (although not present throughout). The Black River Group may also contain occasional sandstone intervals (described as white, quartizitic, and fine grained), as well as dolomite zones with traces of chert. The basal limestone is described as "pure" with little insoluble residue.

The overlying Trenton Formation is composed almost entirely of dolomites that are generally tan to light brown, exhibiting fine to medium crystallinity and are slightly calcareous and cherty. The dolomite is also locally described as light brown to light grey, and is very finely crystalline with scattered vugs and "pin points of hematite red staining". Underlying limestones are described as light grey and chalky to light brown (dense), with stringers of dolomite, with the lower portions described as argillaceous with gray-green shale partings. The Warner-Lambert Well No. 5 was cored in the Trenton limestone interval from 3,620-3,640.5 feet RKB (3,607-3,628 feet BGL). The core is described as a limestone that is brown at the top to gray brown at the base. The cored interval limestone is microcrystalline with stylolites at the top of the core and more micritic at the base, and shaley laminae throughout; the unit contains clasts and is fossiliferous. Terra Tek described the core as a "limestone, brown, microcrystalline, stylolitic with occasional shale laminations, clasts and fossils. The full length of the core appears to be consistent with the above description. Tables B.8-8a and B.8-8b present data obtained from Warner-Lambert Trenton core analyses.

TABLE B.8-8a. TRENTON GROUP CORE DATA, WARNER-LAMBERT WELL NO. 5

		Permeability-Air (md)		Permeability-Fluid (md)	
Plug Interval (ft RKB)	Horizontal Plug Porosity	Ambient Horizontal	Net Overburden Horizontal	Brine Horizontal	Waste Horizontal
3,620-3,621	0.005	0.015	0.014	$9.57x10^{-6}$	----
3,626-3,627	0.004	0.011	0.011	$8.08x10E^{-6}$	----
3,630-3,631	0.003	0.025	0.009	$1.524x10^{-5}$	----
3,635-3,636	0.04	0	0.020	$9.166x10^{-6}$	----
3,640-3,640.5	0.05	0.014	0.014	$5.166x10^{-6}$	----

TABLE B.8-8b. TRENTON GROUP CORE PLUG ANALYSES DATA, WARNER-LAMBERT WELL NO. 5

			Horizontal Permeability (md)		Vertical Permeability (md)
Plug Depth (ft RKB)	Grain Density (g/cm^3)	Porosity	Air	Brine	Injectate
3,620.5	2.736	0.005	0.015	$9.6x10^{-6}$	$1.4x10^{-5}$
3,626.1	2.723	0.004	0.011	$8.1x10^{-6}$	$7.8x10^{-6}$
3,630.5	2.759	0.003	0.025	$1.5x10^{-5}$	$6.7x10^{-6}$
3,632.0	---	---	---	---	$6.2x10^{-6}$
3,635.7	2.723	0.040	<0.01	$9.2x10^{-6}$	$6.8x10^{-6}$
3,640.3	2.730	0.005	0.014	$5.2x10^{-6}$	$5.2x10^{-6}$

The Black River Formation is estimated to be approximately 185 feet thick at the Site, and the Trenton Formation is estimated to be approximately 300 feet. The thickness of the Trenton Formation is based on log data from the W. Van Koevering No. 1 well (Permit 21759), which is the deepest penetration in the AOR that penetrates a portion of the Black River Formation. The Black River Formation thickness is based on log data from the Consumers Energy Zeeland Generating Station wells to the northwest. The Van Koevering well, which has been plugged and abandoned, was drilled 126 feet into the Black River Formation, which is approximately 60 feet above the top of the Prairie du Chien Group, which is the upper confining zone at the Site.

Utica Shale (Confining Zone)

The Utica Shale is present throughout the Site area. The Utica Shale is described as a medium grey to grey-green shale with occasional brown shale partings; some well log cutting descriptions describe the shale as being blue-grey, muddy, and "gummy". The Utica Shale is the confining zone at the nearby Mirant Zeeland wells. The Utica-Trenton contact is abrupt, with the Utica deposited in an open marine environment (Sattler, 2015). Michigan core verifies the marine depositional setting, described as a sometimes fossiliferous grey to black mudsone with pyrite and calcareous lenses. Some vertical fractures were observed in core that were typically cemented with calcite or

gypsum/anhydrite but fracturing was not described as laterally or vertically pervasive (Stattler, 2015). Depositionally, the Utica exhibits shallower-water depositional sequences that are more carbonate and siliciclastic-rich near the top of the unit although this trend is not present in southern or western portions of the Michigan Basin, including Ottawa County. The Utica Shale gamma ray log response is typical of dense mudrock lithologies, and the response is generally consistent throughout the Michigan Basin although thickness may vary (Sattler, 2015).

It is approximately 190-195 feet thick in Zeeland area. Figure B.8-38 is an isopach of the Utica Shale, and Figure B.8-39 is a structure contour map constructed at the top of this shale. Based on the structure contour map, the top of the Utica Shale is estimated to occur at 2,960 ft BSL, or 3,663 ft BGL.

B.8.2.2.4 Silurian, Devonian and Mississippian Units

Devonian and Mississippian-aged units are discussed in Sections B.8.1.3.4 and B.8.1.3.5 of this document. The units include the Undifferentiated Cincinnatian, Manitoulin Dolomite, Cabot Head Shale, Clinton Group, Niagara Group, Salina Group, Bass Islands Group, Detroit River Group, Dundee Limestone, Traverse Group, Antrim Shale, Ellsworth Shale, Coldwater Shale and the Marshall Shale. In total, this interval is estimated to be over 3,400 feet thick at the Site. Figure B.7-4 shows the thicknesses of the Marshall Sandstone within approximately one mile of the Site, which ranges between 0 to 122 feet.

B.8.2.2.5 Glacial Drift

Unconsolidated material of various origins and characteristics are present in the Site area. Figure B.7-4 shows the thicknesses of the Glacial Drift within approximately one mile of the Site, which ranges between 78 to 348 feet.

B.8.2.3 Local Seismic Activity

The Site occurs in a region where only minor occurrences of seismic activity have been detected (USGS, 2017). Figure B.8-21 shows that the Site area is located in an area with low peak acceleration (%g = 4-6). No damage from earthquakes is expected. Based on USGS records (https://earthquake.usgs.gov), only four earthquakes have been recorded in Michigan since 1974 (Figure B.8-40). Table B.8-9 summarizes earthquakes greater than 2.5 magnitude which have occurred within a 200 kilometer mile radius of the Site.

Induced seismicity related to human activity is a concern in localized areas elsewhere in the United States, in places such as Oklahoma and Kansas. The USGS recently published a document identifying the likely location of induced seismic events (Figure B.8-41). As shown in this figure, no areas in Michigan are identified as an area for potential induced seismic activity. Induced seismicity can sometimes be of concern in other areas where significant injection occurs near basement rock. In the case of the Mt.

Simon, Class I disposal wells occur within the states of Michigan and Indiana, many of which have been in operation for decades and are completed throughout the Mt. Simon and at or near basement. None of the seismic events in Michigan or Indiana have been associated with Mt. Simon deep well injection activities.

TABLE B.8-9. EARTHQUAKES >2.5 MAGNITUDE WITHIN 200 KM OF AUTUMN HILLS RDF

Year	Month	Day	North Latitude	West Latitude	Magnitude	Location
1994	09	02	42.798N	84.604W	3.5	Michigan
2012	01	26	41.576N	85.490W	3.0	Indiana
2013	11	04	41.800N	87.825W	3.2	Illinois
2015	05	02	42.236N	85.428W	4.2	Michigan
2015	06	30	42.146N	95.046W	3.3	Michigan

Source: National Earthquake Information Center

B.8.3 Conclusion

Data presented in this section indicate that the Site satisfies the geologic criteria for siting of Class I waste disposal wells by demonstrating that site stratigraphy, structure, hydrogeology and seismicity of the area meet these standards and criteria. Geologic properties are well defined, and as illustrated by geologic characterization and historic operation of neighboring wells, the Injection Zone has sufficient permeability, porosity, thickness and areal extent to accept injectate and prevent migration of fluids into USDWs. Both the Injection Zone and the Confining Zone are laterally continuous and free of transecting transmissive faults or fractures. Further, the Mt. Simon Injection Interval is separated from the top of the Confining Zone by sequences of permeable and less permeable strata that prevent vertical fluid movement. The Confining Zone is also separated from the base of the USDW by multiple sequences of permeable and less permeable strata that serve to prevent vertical fluid movement.

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