OKLAHOMA GAS & ELECTRIC

McCLAIN FACILITY

UIC CLASS I PERMIT RENEWAL APPLICATION

ATTACHMENT B – GEOLOGICAL AND GEOPHYSICAL INFORMATION

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B. GEOLOGICAL AND GEOPHYSICAL INFORMATION

The geologic suitability of a specific stratigraphic interval for the 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;
- Hydrogeologic compatibility of the injected waste stream with formation materials and formation brines;
- Faulting or fracturing of injection reservoir, overlying aquicludes, or confining zone, and
- Seismic risk.

These criteria can be evaluated based on the regional and local depositional and structural histories of the geologic section.

In the following sections, the depositional and structural framework of the sedimentary and hydro-stratigraphic column (Figure B-1) for the injection and confinement of effluent at the Oklahoma Gas & Electric (OG&E) McClain site is outlined. Figures B-2 through B-4 present the cross-sections through the 2.0 mile Area of Review (AOR). Information is obtained from the regional and local data, interpretations, and conclusions of the AOR study, and prior Underground Injection Control (UIC) permits. All depth intervals in this section are reported in log measure depth (MD) unless otherwise noted.

B.1 GEOLOGICAL AND GEOPHYSICAL INFORMATION

B.1.A Regional and Local Geology

The Oklahoma Oil & Electric McClain Facility is located in Township 9 North, Range 4 West, Section 4 on the south bank of the Canadian River in McClain County, Oklahoma. The site is located approximately 12.5 miles south of Oklahoma City, Oklahoma. Interstate Highway 44 lies west of the facility, and the Canadian River forms the northern boundary of the facility. The facility is located approximately 3.5 miles north of the town of Newcastle, Oklahoma. This area of south central Oklahoma is underlain by gently dipping Permian bedrock deeply dissected by numerous small streams and dry creek beds. The Canadian River valley and floodplain dominate the geography around the proposed injection well site. The three-quarter-mile-wide, Pleistocene age valley is largely dry.

Geologically, the site has preserved a very long history. Deep below the surface, at depths in excess of 9,000-feet, there are great thicknesses of hard, tight (non-porous) Early Paleozoic strata that have been deeply faulted and folded. Central Oklahoma's Middle and Late Paleozoic geology is dominated by the southern extension of the Nemaha Ridge, an ancient north-south fault trace approximately 9 miles east of the proposed injection well site that sets up the numerous oil fields around Oklahoma City. Nemaha faulting began early in the Paleozoic and persisted into the Pennsylvanian. After faulting stopped, locally thick sands and shales accumulated. Contemporaneous with the activation of the Nemaha, the Anadarko Basin was a regional area of accumulation. The basin gave rise to the persistent southwest dip and thickening of the Paleozoic strata and the broad persistence of many stratigraphic units that filled the broad marine basin. The final geological event was Pleistocene glaciation far to the north that swelled the Canadian River to many times its present size, enabling it to carve its wide valley and to bring down huge volumes of sand that still fill it.

The OG&E injection well is approximately 2.5 miles southwest of the large West Moore Oil Field, which produces oil and gas from the Hunton, Wilcox, and Lower Pennsylvanian sands (Red Fork, Bartlesville, and Lyle). The location is adjacent to the small Newcastle field that produces oil and gas from the Lower Pennsylvanian, Viola, Wilcox, and Hunton. All production in the area is below the Oswego Formation, which is more than 700-feet below the Oread Formation (lower confining zone). Oil and gas exploration and production has been ongoing in the area for at least 70 years with no indication of any prospective hydrocarbons in the Oread (lower confining zone), Pawhuska (primary injection zone) or Lower Post Oak (upper confining zone) formations.

B.1.B Local Stratigraphy

Local stratigraphy is illustrated on a type-log (Figure B-1) using the OG&E McClain Facility Injection Well WDW-1. The log extends to a depth of 6,890 feet which is more than sufficient to present the proposed Confining and Injection Zones. The top of the Upper Confining Zone (Lower Post Oak Formation) is picked at a depth of 3,868 (-2,570 TVDSS) feet. The top of the Injection Zone (Pawhuska Formation) is picked at a depth of 4,210 (-2,912 TVDSS) feet and the Lower Confining Zone (Oread Formation)) at a depth of 6,826 (-5,528 TVDSS) feet.

The Containment Interval is located at the top of the Pawhuska Formation and is approximately 240 feet thick. It is within the Injection Zone for containment of injected wastes into the underlying Pawhuska sandstones. The sandstones in the overlying Post Oak Formation also provide protection for overlying aquifers and sources of drinking water by acting as buffer aquifers that would allow for bleed-off of pressure and injected wastes. Between depths of approximately 1,800 feet to surface are the Garber-Wellington and the Hennessey listed in ascending order. This stratigraphic section consists of interbedded sandstones, siltstones, and shales.

Subsurface strata beneath the OG&E site are composed of sands, silts, and shales of the Permian age down to a depth of approximately 6,900 feet. The two designated Injection Intervals for the OG&E injection well are contained within the Pawhuska Formation, encountered at approximately 4,566 (-3,268 TVDSS) feet and 6,119 (-4,820 TVDSS) feet, respectively. This local stratigraphy discussion begins with Checkerboard Limestone Formation and then discusses the successive shallower geologic formations.

The lithology of the sedimentary units that are present at the surface and subsurface of the site are typical of units present elsewhere in south central Oklahoma. In the immediate vicinity of the OG&E McClain site, no sediments older than the Oswego Formation have been penetrated by exploratory drilling for oil and gas. The following is a discussion of detailed stratigraphy of individual geologic units between the surface and approximately 6,900 feet beneath the OG&E McClain site (from deepest to shallowest) (Table B-1).

B.1.B.1 Checkerboard Limestone

The Checkerboard Limestone derives its name from its appearance at the surface where it is separated into blocks by two sets of perpendicular joints enhanced by solution channels give it a checkerboard pattern (Bacon, 2010). It is a mixture of shales and marine carbonates that constitute a reliable correlation marker that extends across central and western Oklahoma. In the vicinity of the injection well the Checkerboard is approximately 300 feet thick.

B.1.B.2 Oread Limestone (Lower Confining Zone)

The Oread Limestone (also known as the Oread Limestone of the Vamoosa Group) is a limestone formation, with significant shale members, that is approximately 500 feet in total thickness in the vicinity of the injection well. It contains fossils from the Carboniferous period. The Oread's limestone members are resistant and have been used to historic structures at the University of Kansas. The Oread is a consistent stratigraphic marker through the Area of Review. Figure B-5 presents the structure map of the top of the Lower Confining Zone.

The Checkerboard and Oread strata represent a widespread, low-energy depositional unit; as such, the thick marine shales of the Oread form an ideal seal to effectively isolate the injectate from the underlying oil and gas productive zones in the Lower Pennsylvanian sands and Lower Paleozoic carbonates.

B.1.B.3 Pawhuska (Primary Injection Zone)

The Pawhuska Formation consists of approximately 2,600-feet of gross section and approximately 718-feet (27.5%) of net (greater than 10%) porous white sand interspersed with gray, brittle shale and minor amounts of white sandy limestone. It does not produce oil or gas anywhere in the immediate vicinity but does produce hydrocarbons in the Oklahoma City field, approximately 11 miles northeast of the WDW-1 wellsite. The Pawhuska persists as a thick, sand-rich unit at approximately 3.25 miles southwest of the OG&E injection well.

It is made up mostly of marine sands with intercalated shales. The sands from thick, clean, "barrel-shaped" sand strata, suggesting shore-face or offshore bar facies to thin shaley sand beds suggesting delta-front progradational sequences or tidal-channel splays (Figures B-6 and B-7). In cores the sands range from medium-grained to very fine-grained, quartzose, well sorted arenites with scattered, dark grey shale laminae. Marine fossils are seen occasionally, as are numerous burrows of indeterminant origin. The sands are mostly composed of clean, rounded quartz grains. Cementing agents as seen in cores are silica, calcite, and clay minerals; texture ranges from well cemented to friable. Porosity appears to be strictly intergranular with no fractures or vugs seen in the cores.

The sands have been deposited in mixed marine and non-marine shallow water environments and spread out upon the Permian shelf to the west and the east. Stratigraphically the top of the unit coincides with the top of a widespread thin sand layer.

The sand section within the Pawhuska appears to represent a Permian deltaic feature seaward of a small sediment source bringing terrigenous sandy material to a point near AP 18.

B.1.B.4 Lower Post Oak (Upper Confining Zone)

The lower portion of the Post Oak Formation is a widespread shale unit that rests atop the Pawhuska Formation. It is a massive marine shale with widely scattered thin limestone laminations. The Lower Post Oak formation has notable features of infilled erosional valleys The Lower OG&E injection well site the Lower Post Oak is approximately 375 feet thick (Figures B-8 and B-9).

B.1.B.5 Upper Post Oak

The Upper Portion of the Post Oak Formation is a locally named unit that appears to be stratigraphically equivalent to the Oscar, Vanoss, and Ada Groups described extensively in central Oklahoma outcrops. The Post Oak consists of 2,135 feet of mixed sands and shales. In the area of the proposed injection wells, the Post Oak does not contain hydrocarbons or fresh water.

B.1.B.6 The Garber-Wellington

This formation underlies the thick shales of the Hennessey from approximately 856 feet and extends to approximately 1,810-feet at the injection well location. (Figure B-10). The Garber-Wellington, as seen in the logged interval, is mostly made up of clean, highly porous sands. Most of the sand bodies have sharp tops and bottoms, indicative of deposition in Permian channels and bars. The highest quality of groundwater in the area is produced by the Garber-Wellington and is used by the Oklahoma City municipality. The lowest total dissolved solids values of the Garber-

Wellington aquifer is found at outcrops. In the western part of Central Oklahoma, the Garber-Wellington becomes deeper and its water quality decreases. As is shown in the Hydrologic Cross Section in Figures B-11 and B-12, the Garber-Wellington dips uniformly to the southwest and is filled with progressively higher TDS water as its depth increases.

B.1.B.7 The Hennessey Formation

The Hennessey Formation outcrops at the surface and thickens considerably to the southwest. It extends down to approximately 856 feet. (Figure B-12). The Hennessey is a massive shale with rare, very thin interbeds of sandy shale or limey and low porosity sands. The upper portion of the Hennessey has a lithologically dominated by shale interspersed with thin, hard limestones. This upper portion serves as a regional aquitard, underlying the scattered Quaternary Alluvium, and overlying the Garber-Wellington.

In the lower portion of the Hennessey, there are sands that produce small quantities of fresh water that are considered USDWs. These sand bodies are stacked in fining upward units and appear to be regressive units representing perhaps sand splays onto an interdistributary plain in a mixed marine/fluvial setting. In the AOR the Hennessey aquifers are widely scattered and are poor in quality.

B.1.B.8 Quaternary Alluvium

Although the Quaternary Alluvium is not present in the injection well it is best to mention as it is the topmost of the USDWs within AOR. Depth to water in the alluvium can be less than 20 feet below ground surface (bgs) (Bingham and Moore, 1983). The sands of the alluvium are often saturated with high quality groundwater that is used as a source of drinking water.

Quaternary Alluvium fills the channels of the major river and stream channels in Central Oklahoma It is scattered over the Hennessey formation and lithologically consists of predominantly fine sand to sandy clay.

B.1.C Confining and Injection Zones Characteristics

The following sections include description, log depths, porosity and permeabilities of the Confining and Injection Zones.

B.1.C.1 The Upper Confining Zone (UCZ)

The Upper Confining Zone (UCZ) is the lower portion of the Post Oak Formation immediately overlying the Pawhuska Formation in the vicinity of the proposed injection well. The widespread shale unit that constitutes the UCZ represents the Lower Post Oak Formation and rests atop the Pawhuska Formation. Lithologically, the UCZ is a massive marine shale with widely scattered thin limestone laminations. The top of the UCZ is the erosional base of a significant fluvial sand of variable thickness within the Post Oak Formation; the sand fills dip-wise, southwest-northeast valleys cut into the top of the UCZ. The cut and fill features at the top of the UCZ will not affect the ability of this zone to effectively seal the injectate into the Primary Injection Zone and prevent it from migrating up section into overlying strata. The base of the UCZ is the top of the Pawhuska Formation; as pointed out above, the UCZ is separated by approximately 240 feet of buffer zone that is the upper portion of the Pawhuska Formation.

The UCZ is mostly thick, grayish-brown shale with several thin sands. Of the 240 feet gross interval, fully 191 feet (79.5%) is shale (an isopach map is included as Figure B-8; the structure map is included as Figure B-9). The unit is most suitable as a confining zone to separate the Primary Injection Zone (PIZ) from the higher USDW. Based upon UCZ core that was cut and tested between 3,922 feet (log depth) and 3,996 feet (log depth); the core is mostly hard, gray shale with irregular, sub-horizontal bedding. Shales making up the UCZ are represented by core samples at 3,946 feet, 3,958 feet, and 3,966 feet and their permeabilities are low. Thin, tight, consolidated, clean quartz UCZ sands are represented by samples at 3,928 feet and 3,966 feet showing a range of permeabilities. Several mollusk fossils were seen in the core, suggesting that the formation is at least partly marine. No fracturing was observed in the core or on the log. The average permeability and porosity of the shales of the UCZ are 0.465 millidarcies and 9.8% respectively. Table B-2 presents permeability and porosity results obtained from the core analysis (Appendix B-1).

B.1.C.2 The Lower Confining Zone (LCZ)

The Oread Formation contains the Lower Confining Zone (LCZ). The zone is approximately 500 feet in thickness and the lithology is predominantly indurated marine shale with very few scattered, thin sands and tight limestones. The injection well reached total depth with approximately 72 feet of the LCZ interpreted on the well log (see Figures B-3 and B-4). The top of the zone is the base of the Pawhuska Formation, a widespread sand unit of variable thickness with a sharp, probably erosional, lower boundary. The structure on the top of the LCZ (see Figure B-5) shows a uniform southwestern dip of approximately 150 feet per mile; no faults are seen. The base of the LCZ rests conformably on the top of the Checkerboard Limestone, a mixture of shales and marine carbonates that constitute a reliable correlation marker that extends across central and western Oklahoma. The LCZ and Checkerboard strata represent a widespread, low-energy depositional unit; as such, the thick marine shales of the LCZ form an ideal seal to effectively isolate the injectate from the underlying oil and gas productive zones in the Lower Pennsylvanian sands and Lower Paleozoic carbonates. Injection Zones

B.1.C.3 Pawhuska Injection Zone

The Injection Zone is the Pawhuska Formation, an approximate 2,500-foot thickness of Permian sands and shales. There is one porosity log commercially available on the Eason 1-Billen (AP 24) in the south half of Section 3. This well shows approximately 425 feet of sand in excess of 20-percent porosity. Logs in adjacent sections show abundant sand, but do not have porosity logs. Figures B-13 and B-14 document the structural attitude of the two most capable injection zones. Net sand within the Pawhuska Formation is shown on Figure B-15 (Upper Pawhuska) and Figure B-16 (Lower Pawhuska) as well as net sand trends. The Pawhuska is the Primary Injection Zone (PIZ) for the following reasons:

- Above significant faulting in the area
- Abundant void space (porosity times sand thickness)
- Well separated from deeper oil and gas zones
- Separated by over 3,100-feet of Permian shale from the lowest USDWs.

The Pawhuska Formation consists of 2,590 feet of gross section and approximately 718 feet (27.5%) of net (greater than 10%) porous white sand interspersed with gray, brittle shale and minor amounts of white sandy limestone. It does not produce oil or gas anywhere in the immediate vicinity but does produce hydrocarbons in the Oklahoma City field, approximately 11 miles northeast of the WDW-1 wellsite. The Pawhuska persists as a thick, sand-rich unit at least as far south as 3.25 miles to the southwest.

Lithologically, the PIZ is made up mostly of marine sands with intercalated shales. The sands (as seen on the Cross Sections in Figure B-3 and Figure B-4; (Figure B-2 is the Cross Section location map) vary from thick, clean, “barrel- shaped” sand strata, suggesting shore-face or offshore bar facies to thin shaley sand beds suggesting delta-front progradational sequences or tidal-channel splays (an isopach map is included as Figure B-6). In cores the sands range from medium-grained to very fine-grained, quartzose, well sorted arenites with scattered, dark grey shale laminae. Marine fossils are seen occasionally, as are numerous burrows of indeterminant origin. The sands are mostly composed of clean, rounded quartz grains. Cementing agents as seen in cores are silica, calcite, and clay minerals; texture ranges from well cemented to friable. Porosity appears to be strictly intergranular with no fractures or vugs seen in the cores. The probability of fracturing within the Pawhuska cannot be eliminated but its likelihood is small since the structure maps on the Pawhuska itself and the adjacent formation shows only a shallow, uniform dip. If fracturing were to have been developed, such deformation should be evident as abrupt changes in the structure map at the Pawhuska level.

The sands appear to have been deposited in mixed marine and non-marine shallow water environments. Stratigraphically ,the top of the unit coincides with the top of a widespread thin sand layer. The structure map on the top of the Pawhuska (see Figure B-13) shows a consistent southwestern dip of approximately 150 feet per mile. The upper portion of the Pawhuska PIZ is shaley and does not appear to be hydraulically continuous with the perforated interval. The upper portion of the Pawhuska (4,320 feet to 4,560 feet in the injection well) is included in the PIZ as a buffer between the injection perforations and the UCZ. Porous sand extends almost to the base of the Pawhuska; in the injection well, only the basal ten feet of tight, shaley sand are not perforated. The top of the Upper Pawhuska and the Lower Pawhuska injection intervals are shown in Figure B-15 and Figure B-16, respectively. Figure B-13 and Figure B-14 are net sand maps of the Upper Pawhuska and the Lower Pawhuska injection intervals. Figure B-17 is an isopach map of the perforated thickness in WDW-1. In Figure B-17, the total thickness of the porous interval varies from a thin of 2,028 feet to the thickest value of 2,457 feet. The sand section within the Pawhuska appears to represent a Permian deltaic feature seaward of a small sediment source bringing terrigenous sandy material to a point near AP 18 (Moran Exploration - Sleeper #1). The sands appear to have been spread out upon the Permian shelf to the west and the east.

The Pawhuska PIZ can be split by lithology and reservoir quality into two distinct Injection Intervals:

Upper Sand – 4,560 feet to 5,290 feet

Lower Sand – 6,105 feet to 6,818 feet

B.1.C.3.1 Upper Sand Injection Interval

The Upper Sand unit is 743-feet thick and contains approximately 238-feet (32%) of net porous sand averaging approximately 21% porosity as seen in logs and core analyses (Table B-2). Most of this sand is high quality reservoir. The sands are confined to the lower part of the unit and are closely enough packed to be in pressure communication. Five RFT tests were run in this unit that documented a consistent pressure gradient of approximately 0.413 psi/ft. In cuttings from the well, the sand is fine to very fine grained and loose with slight carbonate cement. The unit also contains significant amounts of tight limestone. The Combinable Magnetic Resonance (CMR) log shows several sands over 1000-md and the majority over 100-md. Core analysis shows an average permeability of 352 md (Table B-2 and Appendix B-1).

Figure B-13 is a map of the structure and Figure B-15 is a net sand map within the Upper Sand Unit. The structure mirrors other stratigraphic units in its southwest dip. The net sand figures are derived from available well logs in the area and are from spontaneous potential (SP) curves and not porosity logs. SP net sand figures are probably proportional to net sand figures derived from porosity logs but the two should not be confused. The net sand map shows variation within the unit from less than 100 feet to over 200 feet of net sand. The thickest net sand appears near the center of the map as a dip-wise string-like feature suggesting its fluvial origin. Away from the thick sand body, the Upper Sand Injection Interval is a mixture of thin sands and shales, suggesting a marine influence. Although the thick sand body is expected to contain the best reservoir, the sand within it will very likely be in communication with surrounding marine sands, which will dissipate the reservoir pressure.

B.1.C.3.2 Lower Sand Injection Interval

The Lower Sand unit is approximately 700 feet thick and contains 388-feet (55%) of net porous sand averaging approximately 18% porosity as seen in logs and core analyses (Table B-2 and Appendix B-1). A significant part of this sand is a capable injection reservoir. There is sufficient sand in the Lower Sand unit for them to be in close pressure communication. Six sands were tested with the RFT, documenting a pressure gradient of approximately 0.436 psi/ft, suggesting that the lower unit sands are hydraulically separate from other upper unit sands. In cuttings the sand appears as very fine-grained and slightly cemented. The unit also contains a small amount of tight, brown, marine limestone with scattered fossils. Several sands displayed permeability's above 1,000-md and most sands were in the interval between 1,000 and 100-md. Core analysis shows an average permeability of 153 md (Table B-2 and Appendix B-1).

Figure B-14 is a map of the structure and Figure B-16 is a net sand map within the Lower Sand Unit. The structure mirrors other stratigraphic units in its southwest dip. The net sand figures are derived from available well logs in the area and are from SP curves and not porosity logs. SP net sand figures are probably proportional to net sand figures derived from porosity logs but the two should not be confused. The net sand map shows variation within the unit from less than 300 feet to over 400 feet of net sand. The thickest net sand appears scattered across the map as dip wise string-like features suggesting a set of stream channels that have filled with sand. Away from the thick sand bodies, the Lower Sand Injection Interval is a mixture of thin sands and shales, suggesting a marine influence. Although the thick sand bodies are expected to contain the best reservoirs, the sands are very likely be in communication with surrounding marine sands, which will dissipate the reservoir pressure.

B.1.C.3.3 Other Possible Injection Zones

Other possible injection zones reviewed include the Post Oak and Oil Creek Formations. Both formations were tested in the surrounding area. The Post Oak was permitted as a Class II (oil and gas wastes) injection zone, but was never used and is much too shallow to be considered a permittable Class I injection zone. The Oil Creek was perforated and tested for injection in the Shenandoah Oil Silver well in the northeast quarter of Section 26 – 10N – 4W. The well took water only briefly and was then plugged. Other possible injection zones (the Hunton, Viola, and Arbuckle) are too deep to be accessed economically and furthermore, the formations produce hydrocarbons in the area.

B.1.C.5 Injection Zone Total Dissolved Solids

Immediately after drilling the OG&E injection well, a Schlumberger Repeat Formation Tester (RFT) sampled water from two Pawhuska sand zones. Water was retrieved from two zones with two samples taken from each zone. In both cases, the zone was flowed to an initial sample chamber to flush the reservoir of as much invading filtrate as possible. The second sample, presumably less invaded, is intended to be more indicative of the reservoir fluid. This two-part sampling process is meant to document invasion and also sample relatively pristine reservoir fluid. Table B-3 gives the analyses of the samples from the two sands.

Logs and water samples suggest that the deeper zone (6,795.05-feet) is deeply invaded with mud filtrate. Resistivity curves for this zone are tightly bunched, indicating significant invasion. Sample #2, taken after the flushing sample, is fresher than sample #1. If the zone had been only mildly invaded, sample #2 would have been significantly higher in TDS than sample #1. We must conclude that the true reservoir fluid was not sampled and its nature is unknown except that its salinity is higher than 96,300 ppm.

The shallower zone (4,920.04-feet) showed the expected analytical progression of sampled water from lower to higher TDS levels. The shallow zone very likely contains reservoir water slightly in excess of 130,000 ppm TDS; maybe as high as 150,000 ppm TDS. A complete chemical analysis from the second sample of reservoir fluid from each depth is shown in Table B-4.

The RFT tool apparently did not sample true reservoir fluid in the deeper sand. The tool most likely did sample nearly pristine water from the shallower Pawhuska sand. The high salinity water from the shallower sand affords us the opportunity to analyze Pawhuska water and calibrate the SP-derived and porosity-derived water calculations.

Salinity from SP logs: The SP trace showed good repeatability but salinities calculated with its values were low to what is most likely the water contained in the sand's pore-spaces. Below are the results of SP log calculations:

Salinity from porosity logs: Porosity logs showed good correspondence with core-derived porosity analyses. Log calculations from the porosity logs in the geologic test well produce salinity values that appear too high for the 4,920-foot sand but are probably within 15% of the true TDS value. The calculation for the lower sand (6,795-feet) appears too high but has an unknown relationship with the reservoir water's true TDS.

B.1.D Hydrogeology

B.1.D.1 Regional Hydrology

The OG&E injection well (WDW-1) and the two Sampling Wells (Sampling Well No. 1 and Sampling Well No. 2) are located in the Central Oklahoma Region. The hydrogeology of the region is dominated by the presence of Quaternary Alluvium and the position of the Hennessey and Garber-Wellington Formations. Quaternary Alluvium fills the channels of the major river and stream channels in Central Oklahoma and is used as a source of drinking water. The Hennessey is a regional aquitard (Christenson and Havens, 1998). The Hennessey outcrops across the southwestern part of central Oklahoma and thickens considerably toward the southwest. From the top of the ground, water first occurs within the Hennessey or in the scattered, overlying Quaternary Alluvium. Depth to water varies considerably across the area from less than 20 feet in the alluvium to greater than 80 feet below ground surface (bgs) within the Hennessey (Bingham and Moore, 1983). Water quality is generally high in the alluvium but variable within the bedrock aquifers. Water quality in the Hennessey and Garber-Wellington Aquifers (as measured by total dissolved solids) diminishes with depth. The highest quality of groundwater is used by the City of Oklahoma City and is found where the Garber-Wellington outcrops are approximately 15 miles to the east. In the western part of Central Oklahoma, the Garber-Wellington becomes deeper (more than 1,000 feet bgs) and its water quality decreases.

B.1.D.2 Local Hydrology

The hydrogeology of the OG&E McClain site area of review is dominated by the Quaternary Alluvium, the Hennessey Formation, and the Garber-Wellington Formation. Quaternary Alluvium is scattered on the surface around the area but is not present at or near the injection well location. Lithologically, the Alluvium consists of predominantly fine sand to sandy clay; the sands are often saturated with high quality groundwater. Groundwater in the unconfined Alluvium aquifer tends to follow the erosional unconformity where the Alluvium rests upon the eroded Permian surface. The flow is towards the Canadian River and then southeast in the area of the facility. The absence of Quaternary Alluvium at the WDW-1 wellsite is shown by the Hydrographic Atlas Figure B-18 of the area (Bingham, 1983) and was corroborated during a field inspection by the Oklahoma Department of Environmental Quality.

Within the area of the AOR, the Hennessey and Garber-Wellington Formations dip southwest at approximately 120 feet per mile, paralleling the deeper strata as shown in Figure B-12 which displays the structural cross section of the Hennessey Formation and Garber-Wellington across the project area. The cross section runs in a roughly dip-wise manner from southwest to northeast. The cross section illustrates the south-west regional dip of the Hennessey, Garber-Wellington, and deeper formations. The cross-section also suggests freshwater infiltration from the northeast. Christensen and Havens (1998) document the same phenomenon at a wider scale by mapping an infiltration point and water dome under Lake Stanley Draper, to the northeast of the area of investigation in Figure B-12. This dome of fresh water has displaced the connate salt water in the Hennessey and Garber-Wellington aquifers, but its ability to displace more saline water decreases with distance away from Lake Draper. Therefore, in the area of the injection well, on the cross-section, the infiltrating fresh water displaces Garber-Wellington connate water down to a depth of a depth of approximately 1,100 feet bgs, but to the southwest becomes less and less able to displace salty connate waters and the base of the lowest USDW moves stratigraphically upward. Note that the Quaternary Alluvium is not shown on cross-section Figure B-12 due to its thinness.

The Hennessey is a regional aquitard at the surface, underlying the scattered Quaternary Alluvium, and overlying the Garber-Wellington throughout the facility vicinity. The Hennessey outcrops throughout the area and thickens considerably to the southwest. The Hennessey is a massive shale with rare, very thin interbeds of sandy shale that give up small quantities of water. In the area of the OG&E WDW-1 well, first water occurs sparsely within the Hennessey. Groundwater in the Hennessey also tends to flow along small fractures in the shale in some areas. Its flow is limited to localized areas where small pockets of water reside. Thin, scattered aquifers in the shallow Hennessey are assumed to be charged by surface infiltration and therefore flow will generally follow topography. Christenson and Havens, 1998, note a diagrammatic map that includes the general vicinity of the wellsite and shows groundwater in the shallow Hennessey following topography (Figure B-19). This publication discusses the paucity of aquifers in the Hennessey and describes it as an aquitard that seals the underlying Garber-Wellington over part of Central Oklahoma, including the area surrounding the wellsite.

Deeper aquifers, including the few sands in the lower Hennessey and the abundant sands in the Garber-Wellington, are all confined by the massive shales in the overlying Hennessey. Figure B-19 corroborates this interpretation with a map of interpreted Garber-Wellington groundwater flow-paths that flow in a general WSW direction at the wellsite. Surface water enters the outcropping Garber-Wellington, causing the hydrologic dome under Lake Stanley Draper, where it moves out radially. Flowing into the vicinity of the WDW #1, the water in the Garber-Wellington is confined by the overlying Hennessey and so is not influenced by the surface effects of the South Canadian River. The driving force to the flow of water in the Garber-Wellington is Lake Stanley Draper that sits over the outcropping Garber-Wellington causing the doming of the potentiometric surface.

The OG&E injection well location is underlain by two water-bearing formations – the Hennessey Formation and the Garber-Wellington Formation. At the well location, there exists approximately 856 feet of Hennessey shale that contains widely scattered, poor quality aquifers. The closest water well to the disposal well location (Map ID No. 72942) is approximately 3,000 feet away as reported by the OWRB (producing interval not reported). Beneath the Hennessey, the Garber-Wellington Formation exists as mixed sands and shales. The Garber-Wellington sands are filled with low-quality water at the top of the formation and high salinity water deeper into the formation.

The Oklahoma Corporate Commission (OCC) and the Oklahoma Department of Environmental Quality (ODEQ) show the bottom of USDWs (i.e., the top of 10,000 mg/L water as shown by SP-bearing sands with greater than 15 ohm-meters of resistivity) at 925 feet below ground surface at the injection well site (Pam Hudson, OCC personal communication). Most wells in the AOR have surface casing set across the base of USDW as required by OCC regulations, therefore few wells in the vicinity of the injection well have a base of USDW picked from logs by the OCC. The OCC does not require wire-line logs be run on the surface hole nor is this standard oilfield practice.

B.1.D.2.1 Base of Lowermost USDW

The base of the lowermost USDW at the injection well site is within Garber-Wellington formation. The deepest sand formation that produced water less than 10,000 mg/L at the site of the WDW-1 well lies between approximately 1,108 and 1,134 feet (log-depth); it produced water containing 8,470 mg/L TDS and shows a deep resistivity of 7 ohm-meters. The 1,125-Foot sand is the deepest sand in the WDW-1 well with resistivity at 7 or more ohm-meters. The base of this sand unit is located at 1,134 feet log-depth and is the base of the lowermost USDW at the WDW-1 injection well. While this sand was only able to produce water at a very low rate (approximately 0.2 gpm), the sand was deemed a USDW by the ODEQ. To identify shallow USDWs containing water less than 10,000 mg/L TDS in offset oil and gas wells within the AOR and to be conservative in our interpretation, any sand with a deep resistivity of 6 ohm-meters or greater was picked as a USDW and the deepest such sand was recorded as the lowermost USDW.

The sand with the deepest 6 ohm-meter deep resistivity was subsequently picked in each well where possible within the AOR. Most oil and gas wells set surface casing according to OCC regulation, which uses the 15 ohm-meter cut-off for the base of USDW, and the 6 ohm-meter level is, therefore below the majority of the surface casing setting depths and appears on logs. The resulting base of USDW data are shown in the Figure B-12 (cross-section of hydrological units) and Figure B-20 (Subsea map of base of USDWs). The depth of the base of USDW map shows approximately 197 feet of depth variation across the AOR. Within the AOR the variability seems to be due to local fine-scale stratigraphic changes, not broad regional changes in the infiltration of fresher water from the recharge areas in the north. In particular, the shaley, thin-bedded sand between 1,108 and 1,134 feet in the WDW-1 well is replaced in parts of the AOR by a thicker sand that appears to be a capable reservoir. Some wells, such as AP10 (Superior Oil Deal Unit #1) contain this clean sand that is greater than 6 ohm-meters of resistivity, defining a base of USDWs that is deeper than most of the surrounding wells. These deep trends are seen as two southwest – northeast, dip-wise trending thickening features that mirror the fluvial nature of the Garber-Wellington.

B.1.D.2.2 Water Wells in the Area of Review

There are a total of 66 water wells (57 domestic, 7 agricultural and 2 observation (the OG&E sampling wells)) and four monitor wells located within or adjacent to the area of review (AOR) as reported by the Oklahoma Water Resources Board (OWRB) in August 2023. The OWRB is charged with maintaining an electronic database of water wells within the state of Oklahoma. The OWRB lists no public water supply wells within the AOR. All 66 water wells are private water wells. The majority of the water wells are completed in the shallow Quaternary Alluvium, with the remainder of the wells completed in the shallow portion of the Hennessey Formation. The disposal well location is well beyond the outcrop of the alluvium. Table B-5 lists the water wells in the AOR on file at the OWRB.

In this area of McClain County, USDWs are, from the surface down, the Quaternary Alluvium, the Hennessey Formation, and the Garber-Wellington Formation. Figure B-20 presents the water wells in the vicinity of the site. The closest water well is Map ID No. 72942 (approximately 3,000 feet to the southeast), which produces water from the Quaternary Alluvium at a depth of approximately 18 feet. The approximate outcrop and sub-crop locations of these aquifers are shown in Figure B-21 (adapted from *Map of the Aquifers and Recharge Areas in Oklahoma*, [Johnson, 1991], which originally appeared as a two-part publication *Maps Showing Principal Ground-Water Resources and Recharge Areas in Oklahoma* [Johnson, 1983]). The 1983 map was a development of Figure B-22 in the *Map Showing Major Sources of Groundwater in Oklahoma*, in Disposal of Industrial Wastes in Oklahoma (Johnson et. al, 1980). According to the 1983 map, the well location is at least one-quarter mile away from the nearest alluvial deposits and is outside the area of the Garber-Wellington principal aquifer and outside of the Garber-Wellington Recharge Area, but are within the potential recharge area of the Garber-Wellington. The author, Ken S. Johnson, describes the 1983 map as having been made from U.S. Geological Survey (USGS) Hydrologic Atlases. Text shown on the Johnson 1983 map states the following:

> *"Potential recharge areas shown on the accompanying map include the following: (1) areas where an aquifer is overlain by confining strata that may contain natural or artificial pathways that could permit downward movement of surface water to the aquifer, and (2) additional safety zones that generally extend 4 miles beyond the known limits of an aquifer. The safety zones extend an arbitrary, yet conservatively reasonable distance from the aquifers: they include areas that may possibly have a hydrologic impact on the recharge of the aquifer as well as those areas that may overlie unknown lateral extensions of the aquifer."*

According to the author, the potential recharge zone was an arbitrary buffer zone around the bedrock aquifer that was intended to allow for possible local outliers, fractures, and open boreholes that could conduct surface water into the main aquifer or could locally change aquifer limits (Johnson, personal communication, 2000).

Additionally, the map was augmented for the Garber-Wellington Aquifer by Christenson and Havens in Groundwater Quality Assessment of the Central Oklahoma Aquifer (1998). This report redefined the extent of the Garber-Wellington Aquifer and its recharge zone. The USGS paper shows no Garber-Wellington Aquifer recharge from the south side of the Canadian River. One of the principal USGS researchers, Scott Christiansen, describes the Garber-Wellington Aquifer in this part of McClain County as containing very low quality water, too salty for use as human or livestock drinking water. Furthermore, hydraulic head within the Garber-Wellington documents that this part of the aquifer is not recharging to the main body of the aquifer that does carry drinkable water (Christenson, personal communication, 2000).

Oil and gas activity in the vicinity of the injection well has generated a great deal of high-quality data relevant to hydrogeology. These data can be used to clarify the local hydrological picture. The following are basic hydrological facts about the site:

- Figure B-11 displays the location of the structural cross-section in Figure B–12 where the Hennessey-Garber contact shows approximately 120 feet of southwest dip per mile, paralleling the deeper strata.
- Base of the local USDW (less than 10,000 ppm) derived from wireline geophysical logs calibrated by aquifer production tests is 1,116 feet below ground-surface at the location of the Class I injection well, subsea-level map of the base of the USDW is shown in Figure B-19.
- At the location of WDW-1 the top of the Garber-Wellington Formation is at 856 feet log-depth (subsea-level map of top of Garber-Wellington Formation is shown in Figure B-10). The shallowest Garber sand – the 900-foot sand – was perforated and tested in the Sampling Well #1 where it produced 4,000 mg/L water. The deepest tested Garber aquifer in the vicinity of the WDW-1 well is at 1,380 feet where it was sampled in Sampling Well #2; produced water tested 103,000 mg/L. The Garber sands below this depth contain waters with even higher salinities. Groundwater sampling results are presented in Table B-6.
- The nearest water well completed in the Garber-Wellington Formation is over 7.5 miles to the northeast in the town of Moore as plotted by Christenson and Havens, 1998. The increased

depth, the low water quality even in the upper part of the Garber-Wellington (900-foot sand) at the vicinity of the disposal well and the presence of very saline water in the 1,385 foot sand confirms that it does not meet the definition of either a "principal aquifer" nor a "recharge area" as contained in OAC 252:652 Subchapter 3.

- The Hennessey Shale overlies the Garber-Wellington in the area of the injection well. This shaley interval is 858 feet thick and will prevent surface water in the vicinity of the AOR from percolating downward into the Garber-Wellington Formation.

The Garber-Wellington contains a mixture of medium and high TDS water beneath this location and does not recharge the drinkable portion of the aquifer that is located north and east of this AOR. The presence of the thick shale interval above the Garber-Wellington prevents any recharge from surface or subsurface water percolation. This data supports that the injection well is located outside of the recharge area for the Garber-Wellington Formation and is permittable under Oklahoma DEQ rules (OAC § 252:652-3-1 et seq).

B.1.E Geologic Structure of the Local Area

The OG&E McClain injection well site lies on the eastern flank of the Anadarko basin, a major structural basin covering all of western Oklahoma north of the Wichita Mountains. At the north the area includes the southern limit of the Nemaha ridge, a major line of buried folding and faulting which extends from central Oklahoma northward into Nebraska. The northern part of the area shows the effect of the Oklahoma City uplift, the greatest of all Nemaha Ridge structures. The southeastern part of the area borders the Pauls Valley uplift which is closely related to the Arbuckle Mountains (Jacobsen, 1949). The structure of the area is characterized by a thick sequence of regionally southwesterly gently dipping sediments and sedimentary rocks.

B.1.F Geological Cross-Sections

A cross section location and index map (Figure B-2) and two perpendicular structural cross sections (Figures B-3 and B-4) were constructed to characterize the subsurface structure and stratigraphy in the vicinity of the Area of Review. The sections show the lateral continuity of the injection intervals and the lithologic character of both the confining portion of the injection zone and the upper and lower confining zones across the area. The confining units are sufficiently impermeable, thick, and laterally extensive to protect all strata above and below the injection interval from contamination by injected wastes.

B.1.G Faults And Fracture Systems

Deep drilling in McClain County has shown evidence of a fault zone of linear displacement. This zone is appropriately named the McClain County Fault Zone (MCFZ). The fault extends through the county from north to south. The MCFZ is considered to be a boundary between the Anadarko Basin on the west and the Central Oklahoma Platform on the east (Jacobsen, 1949). Faulting can be seen at the Hunton level (approximately 7,500-feet bgs) within the West Moore field. Similar faulting is expected though not observed in the Newcastle field, although at a smaller scale. The faulting at West Moore is not, however, expressed above the Pennsylvanian unconformity. In the area of the injection well, there is no faulting seen in well control at the LCZ, PIZ, or UCZ levels. (Figures B-3 and B-4).

B.1.H Seismic Activity

B.1.H.1 Regional Seismicity

In any particular region, the level of earthquake hazard depends on many different factors. These include the size, location, and frequency of earthquakes that may occur, as well as the population density, the topography, and the nature of manmade improvements. For any particular earthquake the expected intensity also depends on the type of construction and the thickness and type of surficial and near-surface soil. For any region, the most important factor affecting seismic risk is the historical record of earthquake activity. Regions that have had large earthquakes in the past will likely experience them again. Although hazard estimates also include information about mapped faults, in practice this information isn't very influential since many known faults are not seismically active, and since many damaging earthquakes have occurred along unmapped, unknown faults.

Thus, it is no accident that the regions of highest hazard in United States Geological Survey's (USGS) hazard analysis correspond to the locations of known, large, historical earthquakes (see Figure B-23). In the central U.S., the USGS assesses the greatest hazard in the Missouri-Tennessee area, where three earthquakes with magnitude of 8 or greater occurred in 1811 and 1812.

Unfortunately, the very rarity of large earthquakes makes hazard analysis an inexact science. In the twentieth century, the largest earthquake in the Missouri-Tennessee area only had a magnitude of about 5.5.

In Oklahoma, the regions at greatest risk are in Northeastern Oklahoma near the New Madrid Fault in the Missouri Boot Heal and in Southwestern Oklahoma near Lawton where the Meers Fault is located near the Panhandle area of Texas, where at least six earthquakes with magnitude above 4 have occurred since 1900. Earthquakes of similar magnitude may occur again. Geologically, some features of the Panhandle are similar to the Missouri-Tennessee area, however, large continental quakes are extraordinarily rare (occurring less often than once per 500 years in any particular place). The frequency of small and large earthquakes are related in a predictable way; the "Gutenberg-Richter relation" states that for every 1000 magnitude 4 earthquakes there will be approximately 100 magnitude 5 events, ten magnitude 6 events, and one magnitude 7 event. Thus, the occurrence of two earthquakes with magnitude near 6 in the twentieth century suggests that a magnitude 7 may occur every few hundred years or so. However, like many other "rules of thumb", the predictions of the Gutenberg-Richter relation aren't always correct.

B.2.H.2 Earthquake History of Oklahoma

An earthquake is a motion or trembling that occurs when there is a sudden breaking or shifting of rock material beneath the earth's surface. This breaking or shifting produces elastic waves which travel at the speed of sound in rock. These waves may be felt or produce damage far away from the epicenter: the point on the earth's surface above where the breaking or shifting actually occurred.

In Oklahoma, ten widely separated seismograph stations record the ground motion due to earthquakes. Approximately fifty minor earthquakes are recorded in Oklahoma each year, of those fifty only a few are typically felt. The first seismographs were installed in 1961. Before this installation, only fifty-nine earthquakes were know from seismographs in other states or historical record. Seventy earthquakes were added to the Oklahoma earthquake database between 1962 and 1976. With nine seismographs online, over 2,000 earthquakes were recorded in Oklahoma from 1977 to 2009. Beginning in 2009, the frequency of earthquakes jumped from one or two 3.0+ magnitude per year to hundreds. Since 2009 thousands of earthquakes have been recorded in

Oklahoma, North Texas and southern Kansas. Katie Keranen, a seismologist at the University of Oklahoma, published a peer-reviewed article in the scientific journal *Geology*, in 2013, stating a relationship between fluid injection and seismicity. In 2015 The Oklahoma Geological Society released a "Statement on Oklahoma Seismicity." This statement concluded that "The primary suspected source of triggered seismicity is not from hydraulic fracturing, but from the injection/disposal of water associated with oil and gas production."

Significant earthquakes in Oklahoma are summarized in the following paragraphs:

> October 22, 1882 - the earliest earthquake was felt in the current Oklahoma boundaries, presumed to be near Fort, Gibson, Indian Territory. "The *Cherokee Advocate* reported that at Fort Gibson "the trembling and vibrating were so severe as to cause door and window shutters to open and shut, hogs in pens to fall and squeal, poultry to run and hide, the tops of weeds to dip, [and] cattle to lowe."" (Oklahoma Historical Society)
>
> December 2, 1897 – the first "locatable" earthquake occurred near Jefferson in Grant County.
>
> April 9, 1952 - A magnitude 5.5 earthquake occurred near El Reno in Canadian County. This created a fifty-foot crack in the Capitol building in Oklahoma City. The total area that felt the earthquake was around 140,000 square miles, felt throughout Oklahoma and parts of seven states as far north as Iowa.
>
> November 5, 2011 - magnitude 4.8 earthquake occurred east of Oklahoma City between Prague and Sparks. Less than a day later, an earthquake centered near the same location, with a magnitude 5.6 (later upgraded to a 5.7 by the USGS), occurred, damaging homes and the Benedictine Hall at St. Gregory's University in Shawnee. Minor quakes were recorded prior to these major earthquakes. Numerous aftershocks were recorded, several with a magnitude of 4.0. The USGS concluded, in 2016, that the primary cause of these earthquakes was pressure on faults due to the effects of high pressure injection of waste waters from oil and gas production.
>
> September 3, 2016 - A magnitude 5.8 earthquake was centered in Pawnee County Oklahoma. This earthquake was felt up to distances of 1,500 km from the epicenter. Severe

damage occurred to dozen of buildings and is to date the state's largest earthquake. It is suspected that this earthquake was the result of wastewater injection.

Table B-7 presents a summary of naturally occurring earthquakes, including the seismicity in and around McClain County, Oklahoma. A database search within a 25-kilometer radius from the McClain Facility using the National Earthquake Information Center (part of the USGS) to locate nearby earthquakes was conducted in August 2023 (Figure B-24). The search shows twenty five low magnitude earthquakes were recorded within 25 kilometers of the OG&E site (occurring to the south and west) since 2005.

B.2.H.3 Induced Seismicity

Since 2010, the occurrence of earthquakes with a magnitude greater than 3.0 have increased from twenty events per year (1967-2000) to over one hundred events per year (2010-2013) in the central and eastern US region (Ellsworth, 2013). This rate peaked with 1,010 earthquakes in 2015. The rate has since declined, with 130 magnitude 3.0 or greater earthquakes recorded in the same area in 2019. The increased rate of occurrence in previously inactive seismic areas has been correlated with the increased use of injection wells. Many of these wells are located near faults. Fluid injection induced earthquakes are most likely caused by the increased pore pressure from injection operations which have reduced effective stress of faults leading to failure. This mechanism has been used to explain the best-known cases of injection-induced seismicity which was first studied in the Rocky Mountain Arsenal near Denver in the 1960s. New case studies have documented, with the increasing use of wastewater injection wells associated with hydraulic fracking. At many sites, smaller seismic occurrences have shown to be precursors to larger events. More data has become available since the Rocky Mountain study in the 1960s, leading to a better understanding of factors and processes associated with induced-seismicity.

Factors for an induced earthquake are limited to the distance a well is located from a fault, the stress state of the fault, and a sufficient quantity of fluids from the injection well at a high enough pressure and enough time to cause movement along the fault (Ohio Department of Natural resources, 2012). A hydraulic conduit from the injection zone to a fault may also induce earthquakes (Ellsworth, 2013). The largest injection-induced events are associated with faulting that is deeper than the injection interval, suggesting that the increased pressure into the basement increases the potential for inducing earthquakes (Ellsworth, 2013). In all cases, faults have been reactivated at or in close proximity of Class II injection sites. In some cases, previously unknown faults have been discovered. No induced earthquakes have been known or are postulated to have been caused by Class I injection operations (Davis et al., 1987).One of the most notable regional cases of induced seismicity associated with injection wells occurred in Youngstown, Ohio. In 2011, twelve low-magnitude seismic events occurred along a previously unknown fault line (Ohio Department of Natural Resources, 2012). These events occurred less than a mile from Class II injection well Northstar I. Previously, the area was seismically inactive. Earthquakes began a few months after the initiation of injection of wastewater. The allowable wellhead injection pressure at Northstar I was increased twice over 6 months (Ohio Department of Natural Resources, 2012) and may have reduced the effective stress on the fault. After the well was shut down by the Ohio Department of Natural Resources, the seismic activity declined. As a result of this case, seismic monitoring prior to injection and after injection has become common in Ohio Class II sites.

A case study in the Dallas-Fort Worth (DFW) area tied small seismic events to a Class II injection well. Eleven hypocenters have been observed at a focal depth of 4.4 km and 0.5 km from a deep saltwater disposal (SWD) well (Frohlich et al., 2013). Injection at this well began 8 weeks prior to the first recorded seismic event. A northeast trending fault is located approximately at the same location of the DFW focus (Frohllich et al., 2013). As a result of fluid injection into the disposal well, the stress upon the fault had been reduced and thus reactivated the fault (Frohlich et al., 2013). All of the seismic events associated with the DFW focus are small magnitude events (less than 3.3) and occurred very shortly after initial injection.

In north-central Arkansas, multiple earthquakes have been triggered as a result of a Class II injection well. Since the operation of the disposal well began in 2009, the site has experienced an increase from two events in 2008 to 157 events in 2011 (Horton, 2012). It was also tied to the discovery of a new vertical fault. Ninety-eight percent of earthquakes within this area occurred within six kilometers of one of three waste disposal sites (Horton, 2012). The depth of the earthquake foci occurred between 6.7 and 7.6 km. Injection of fluid occurred at a depth of 2.6 km. At this disposal site, an E-W trending (Enders Fault) cut into the aquifer in which the fluid was injected and then acted as a conduit to the new fault at the depth of 6.7 to 7.6 km (Horton, 2012).

The disposal wells were shut down in 2011 by the Arkansas Oil and Gas Commission. The rate and size of the earthquakes steadily decreased following the shutdown of the wells (Horton, 2012).

Historically, induced earthquakes in Texas have not exceeded a magnitude of 4.6 (Frohlich et al., 2013). However, there have been two recent occurrences in Mentone, Texas. In 2020 a magnitude 5.0 earthquake occurred and in 2022 a magnitude 5.3 earthquake occurred. This 5.3 magnitude earthquake is the third strongest in Texas history. Mentone is located in the Delaware Basin, between Reeves and Culberson Counties. This event was most likely induced by wastewater disposal operations. (Skoumal et al. (2018) et. al, 2021). In Texas there are at least two other known examples of previously seismically inactive areas becoming seismically active after major injection programs began. One site is located in the Central Basin Platform, near Kermit, and the other is in the Midland Basin near Snyder. In both cases, large scale, high pressure, oil field related, water flooding projects were under way, and earthquakes with a magnitude of over 4.0 on the Richter scale were recorded.

In Oklahoma, the largest earthquakes in the state's history may have been the results of wastewater injection at a Class II disposal sites. In September 2016, a site near Pawnee Oklahoma was the location of a 5.8 magnitude earthquake that followed a short period of aftershocks. Additionally, a 5.7 magnitude earthquake occurred in 2011 in Prague, Oklahoma, which may have been the result of Class II activities. Wastewater had been pumped continuously into an old oil well for 17 years. As the pore spaces filled, the wellhead pressure was increased to continually inject the wastewater. This reduced the effective stress upon the Wilzetta fault located 650 meters from the well (Keranen et al., 2013). The fluid was injected into the same sedimentary strata at which 83% of the aftershocks originated (Keranen et al., 2013). In this case, the seismic event occurred years after the initial injection phase. Since the area was considered low risk seismically, there is no data on smaller earthquakes that may have proceeded the event in 2011. There has been significant induced seismic activity to the south and northeast of the OG&E site (south central Oklahoma) with a few incidents in the surrounding area of McClain County (Figure B-25).

B.2.H.4 Seismic Risk

At the OG&E site, the probability of an earthquake caused by natural forces or fluid injection is considered remote. Low injection pressures at the plant site into unconsolidated, high-porosity/high-permeability sands over a broad area, within an area not subject to natural earthquakes, are unlikely to induce an earthquake. Therefore, the probability of an earthquake of sufficient intensity to damage the injection system, injection well, or the confining layer is also considered low. Detailed information about the calculated induced seismicity for the site is included in the Seismic Risk Assessment in Section B.2.H.5.1

B.2.H.5 Local Seismicity

B.2.H.5.1 Seismic Risk Assessment of Area of Review

A seismic assessment for the OG&E McClain facility is based upon historical seismic activity for the local area, locations of local faults and fractures, current injection activity in the area, and the thickness and compaction of the sediments and strata within the Area of Review.

The potential for induced seismicity at the OG&E McClain site can be evaluated using the very conservative "zero-cohesion Mohr-Coulomb failure criterion" recommended by the U.S. Geological Survey (Wesson and Nicholson, 1987). This method is based on the following equation:

$$P_{crit} = \frac{S_v(3\alpha - 1)}{2} \tag{1}$$

where:

P_{crit} = the critical injection zone fluid pressure required to initiate slippage along faults and fractures

S_V = the total overburden stress (which represents the maximum principal stress in the Gulf Coast region)

α = the ratio of the minimum principal stress (horizontal in the Gulf Coast region) to the maximum principal stress (overburden stress)

Inherent in Equation (1) are a number of conservative assumptions; these assumptions are applied to produce a worst-case lower bound to the critical fluid pressure for inducing seismicity. These assumptions are:

1) Neglect the cohesive strength of the sediments.

2) Assume that a fault or fracture is oriented at the worst possible angle.

3) Assume a worst-case (minimum) value of 0.6 for the coefficient of friction of the rock (see Figure 4 of Wesson and Nicholson, 1987).

For present purposes, Equation (1) can be expressed in a more convenient form by introducing the so-called matrix stress ratio (K_i) (Matthews and Kelly, 1967; Eaton, 1969), which is defined as the ratio of the minimum to the maximum "effective" principal stresses. Effective principal stress is equal to actual principal stress minus fluid pore pressure (p_o). Thus:

$$K_i = \frac{\alpha S_v - p_o}{S_v - p_o} \tag{2}$$

Substituting Equation (2) into Equation (1) yields:

$$\Delta P_{crit} = \left(\frac{3K_i - 1}{2} \right) \left(S_v - p_o \right)$$

where ΔP_{crit} is the critical injection zone pressure buildup required to induce seismicity, with:

$$P_{crit} = p_o + \Delta P_{crit} \tag{3}$$

Equation (3) is used to evaluate induced seismicity at the OG&E McClain facility.

Reservoir Mechanics indicates the initial pore pressure (p_o), at the injection depths, is 0.4232 pounds per square inch per foot of depth (psi/ft) at the reference depth of 4,566 feet below ground level as reference in Injection Well No. 1 (WDW-1). Eaton (1969) provides a plot of the effective overburden stress (S_V) as a function of depth. This plot indicates S_V values exceed 0.90 psi/ft for the injection interval reservoirs. Matthews and Kelly (1967) provide a plot of the matrix stress ratio (K_i) for tectonically relaxed reservoir sediments. This plot indicates that, at all depths greater than 4,566 feet, K_i exceeds a value of 0.68. The induced seismicity gradient in 0.189 psi/foot of depth and the ΔP_{crit} for the Upper Pawhuska Sand (upper most injection interval) in the injection well is calculated as an incremental pressure increase of 861 psi at the most conservative depth.

The modeled predicted pressure contour plots presented in Reservoir Mechanics (Figures 2, 3 and 4) show that the critical pressure isopleth required to induce seismicity is contained within the wellbore, even when modeled with maximum requested injection rates. Since there are no known faults or fractures within the Area of Review, induced seismicity will not be a problem at the OG&E McClain facility.

B.2.H.5.1 Local Seismic History

Seismic activity in the area has been historically and currently very low. An earthquake search performed in 2023 for seismic events within 100-kilometer of the OG&E McClain facility contained in Table B-7. The closest seismic event occurred on October 10, 2017, approximately 5.5 miles from the OG&E site (near Bridge Creek, Oklahoma) with a magnitude of 2.6.

B.1.I UIC Well Location Criteria

The following information regarding the UIC well location criteria is taken in its entirety from the original *UIC Permit to Operate Application* submitted in 2012 (water well information updated with 2023 ODRB data). The well location criteria must be met for a proposed Class I injection well. All location criteria for well siting were previously documented in the original application and a *Permit to Operate* was granted by the ODEQ on May 26, 2014.

Oklahoma Regulations

The Oklahoma Administrative Code Volume 252:652, Subchapter 3, "lists the following four criteria that must be satisfied for construction of any prospective Class I injection well:

- **Groundwater Resources and Recharge Areas.** Except as otherwise provided by Title 27A O.S. Supp. 1994, § 2-7-111, no permit for a proposed new site shall be granted for a Class I injection well facility to be located over or through an unconsolidated alluvial aquifer or terrace deposit aquifer or over or through a bedrock aquifer. Site-specific hydrological and geological information, which demonstrates that the location does not lie in a prohibited area, may be provided by the applicant. The Department may require site-specific hydrological and geological information for a facility proposed to be located outside a designated principal groundwater aquifer or recharge area where there is reason to believe the proposed location may be unsuitable due to localized groundwater conditions. Sources used to determine if a site is un-permittable include the *Map of Aquifers and Recharge Areas in Oklahoma*, compiled by Kenneth S. Johnson, Oklahoma Geological Survey (1991), and the OWRB rules codified at OAC 785.45 Appendixes A through D, inclusively, or any successor map (s) to these sources.

- **Water Wells.** No permit shall be granted for a new Class I injection well facility proposed to be located within 1,320 feet (one-quarter statute mile) of any public or private water supply well.

- **Flood Plain.** No new Class I injection well facility shall be permitted in the 100-year floodplain unless the 100-year floodplain is subsequently redefined to not include the land area proposed for the new disposal area.

- **Surface Water.** Except as provided by OAC 252:635-3-7(c), no permit shall be granted for a new Class I injection well facility proposed to be located within the established conservation pool elevation of any reservoir which supplies water for a public water supply.

Response to Criterion #1: Groundwater Resources and Recharge Areas

The DEQ regulations specifically prohibit injection through the alluvial aquifer, the alluvial aquifer recharge area, or the principal bedrock aquifers. The intent of the regulations appears to be that mapped recharge areas must be avoided or reconciled with local hydrological and geologic data.

The location of the injection well (see Figure B-27) is clearly outside of the alluvial and bedrock areas, but is shown to be located within the potential recharge area of the bedrock aquifer as identified on the Oklahoma Geological Survey map of aquifers and recharge areas of Oklahoma (Johnson, 1991). Abundant local data support OG&E's contention that the well location is outside of the area of principal bedrock or alluvial aquifers and is also outside the area of active recharge to the local aquifers. The regulations allow for the presentation of site-specific hydrological and geological data to support OG&E's position that although the site is shown to be inside the recharge area on the map, the site is not located within the recharge area according to the information gathered in the area adjacent to the disposal well site.

- In this part of McClain County, USDWs are, from the surface down, the Quaternary Alluvium, the Hennessee Formation, and the Garber-Wellington Formation. Figure B-21 shows the water wells in the vicinity of the site; Table B-5 lists these wells. The closest water well to the disposal well location (Map ID No. 72942) is approximately 3,000 feet away as reported by the OWRB (producing interval not reported). The approximate outcrop and sub-crop locations of these aquifers are shown in Figure B-23 (adapted from *Map of the Aquifers and Recharge Areas in Oklahoma*, [Johnson, 1991], which originally appeared as a two-part publication *Maps Showing Principal Ground-Water Resources and Recharge Areas in Oklahoma* [Johnson, 1983]). The 1983 map was a development of Figure 6 in the *Map Showing Major Sources of Groundwater in Oklahoma*, in Disposal of Industrial Wastes in Oklahoma (Johnson et. al, 1980). According to the 1983 map, the well location is at least one-quarter mile away from the nearest alluvial deposits and is outside the area of the Garber-Wellington principal aquifer and outside of the Garber-Wellington Recharge Area, but are within the potential recharge area of the Garber-Wellington. The author, Ken S. Johnson, describes the 1983 map as having been made from U.S. Geological Survey (USGS) Hydrologic Atlases. Text shown on the Johnson 1983 map states the following:

"Potential recharge areas shown on the accompanying map include the following: (1) areas where an aquifer is overlain by confining strata that may contain natural or artificial pathways that could permit downward movement of surface water to the aquifer, and (2) additional safety zones that generally extend 4 miles beyond the known limits of an aquifer. The safety zones extend an arbitrary, yet conservatively reasonable distance from the aquifers: they include areas that may possibly have a hydrologic impact on the recharge of the aquifer as well as those areas that may overlie unknown lateral extensions of the aquifer."

According to the author, the potential recharge zone was an arbitrary buffer zone around the bedrock aquifer that was intended to allow for possible local outliers, fractures, and open boreholes that could conduct surface water into the main aquifer or could locally change aquifer limits (Johnson, personal communication, 2000).

Additionally, the map was augmented for the Garber-Wellington Aquifer by Christenson and Havens in Groundwater Quality Assessment of the Central Oklahoma Aquifer (1998). This report redefined the extent of the Garber-Wellington Aquifer and its recharge zone. The USGS paper shows no Garber-Wellington Aquifer recharge from the south side of the Canadian River. One of the principal USGS researchers, Scott Christiansen, describes the Garber-Wellington Aquifer in this part of McClain County as containing very low quality water, too salty for use as human or livestock drinking water. Furthermore, hydraulic head within the Garber-Wellington documents that this part of the aquifer is not recharging to the main body of the aquifer that does carry drinkable water (Christenson, personal communication, 2000).

Oil and gas activity in the vicinity of the injection well has generated a great deal of high-quality data relevant to hydrogeology. These data can be used to clarify the local hydrological picture. The following are basic hydrological facts about the site:

- Figure B-11 displays the location of the structural cross-section in Figure B-12 where the Hennessee-Garber contact shows approximately 120 feet of southwest dip per mile, paralleling the deeper strata.

- Base of the local USDW (less than 10,000 ppm) derived from wireline geophysical logs calibrated by aquifer production tests is 1116 feet below ground-surface (bgs) at the location of the Class I injection well, subsea-level map of the base of the USDW is shown in Figure B-20.

- At the location of WDW-1 (SW/4 Section 4–9N–4W), the top of the Garber-Wellington Formation is at 856 feet log-depth (subsea-level map of top of Garber-Wellington Formation is shown in Figure B10). The shallowest Garber sand – the 900-foot sand – was perforated and tested in Injection Well #1 where it produced 4000 mg/L water. The deepest tested Garber aquifer in the vicinity of the WDW-1 well is at 1380 feet where it was sampled in Sampling Well #2; produced water tested 103,000 mg/L. The Garber sands below this depth contain waters with even higher salinities.

- The nearest water well completed in the Garber-Wellington Formation is over 7.5 miles to the northeast in the town of Moore as plotted by Christenson and Havens, 1998. Details of perforated and tested intervals in the immediate vicinity of the WDW-1 well are listed in Table B-5. The increased depth, the low water quality even in the upper part of the Garber-Wellington (900-foot sand) at the vicinity of the disposal well and the presence of very saline water in the 1,385 foot sand confirms that it does not meet the definition of either a “principal aquifer” nor a “recharge area” as contained in OAC 252:652 Subchapter 3.

- The Hennessee Shale overlies the Garber-Wellington in the area of the injection well. This shaley interval is 858 feet thick and will prevent surface water in the vicinity of the AOR from percolating downward into the Garber-Wellington Formation.

The Garber-Wellington contains a mixture of medium and high TDS water beneath this location and does not recharge the drinkable portion of the aquifer that is located north and east of this AOR. The presence of the thick shale interval above the Garber-Wellington prevents any recharge from surface or subsurface water percolation. This data supports that the injection well is located outside of the recharge area for the Garber-Wellington Formation and is permittable under Oklahoma DEQ rules (OAC § 252:652-3-1 et seq).

Response to Criterion #2: Water Wells

The closest water well to the disposal well location (Map ID No. 72942) is approximately 3,000 feet away as reported by the OWRB (producing interval not reported). Figure B-21 is a map of water wells within the AOR as listed by the OWRB.

Response to Criterion #3: Flood plain

The disposal well location (SW/4 Section 4–9N–4W) is over 1.5 miles beyond the floodplain of the Canadian River; the boundary of the floodplain nearest the location is approximately 1,160-feet above sea level, approximately 120-feet below the elevation of ground level at the well.

Response to Criterion #4: Surface water

The location (SW/4 Section 4–9N–4W) is located far outside any conservation pool of any reservoir.

B.2 PROPOSED FORMATION TESTING PROGRAM

The original permit application requested permission to convert the previously drilled geologic test well (WDW-1) to a Class I non-hazardous injection well. The geologic test well was previously approved for construction and subsequent testing by ODEQ. The well was drilled, developed, and tested at the injection facility located approximately 2.5 miles from the McClain Facility.

The request to drill the test well contained a detailed drilling and testing procedure that was reviewed and approved by ODEQ. The approved drilling and testing procedure is presented in Section 2 of Attachment C – Appendix A. Section 3 of Appendix C contains details on the actual well drilling and testing activities. The well was drilled and initially tested during May and June 2000.

The fluid pressure, temperature, fracture pressure and physical/chemical characteristics of the formation fluids are discussed in Attachment A – Part II - Reservoir Mechanics.

Open hole logs and lab results of core and fluid testing are contained in Attachment C –Well Construction.

Ambient falloff pressure testing has been conducted annually since the installation of the well.

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