Evaluation of the Class VI Application Narrative for
Wabash Valley Resources Class VI Permit Application

This site characterization evaluation report for the proposed Wabash Carbon Services (WCS) Class VI geologic sequestration project summarizes the geologic evaluation and data submitted by the applicant in the permit application narrative report per 146.82(a). This report describes and evaluates the available data on which the UIC permit application for the proposed Class VI wells are based and identifies uncertainties that will need to be addressed via the pre-operational testing that will be performed before the applicant will receive an authorization to inject CO_2. It reflects the organization of WCS's permit application narrative document. Clarifying questions for WCS are provided in blue within the text below.

There is some overlap in the information provided in the permit application narrative and WCS's AoR and Corrective Action Plan (AoR CA); where WCS provided identical/similar discussion, reference to the companion review of the AoR modeling is provided, rather than duplicate the review. Likewise, reference to additional plans submitted to the GSDT is outside the scope of this review.

Project Background

Wabash Carbon Services (WCS) will develop a carbon sequestration project that will inject 1.67 million metric tons of CO_2 per year into the Potosi Dolomite injection zone at a depth of approximately 4,600 ft MD (4,100 ft TVDss). The Potosi Dolomite is part of the Knox Supergroup. The site specific and regional data discussed in the application is based on the stratigraphic test well Wabash #1, drilled in 2019 near the site of the proposed injection wells.

The Maquoketa Group, also known as the Maquoketa Shale, is proposed to be the primary confining unit, based on regional extent and permeability data derived from nearby core samples. However, there are multiple low permeability zones within the Knox Supergroup beneath the Maquoketa Group. The Maquoketa Group ranges in depth from 2,386 ft MD (1,836 ft TVDss) to 2,700 ft MD (2,150 ft TVDss). No faults or fractures were identified in the Wabash #1 well or seismic analysis of the site.

There will be two injection wells at the injection site, Geologic Sequestration Well #1 (WVCCS1) and Geologic Sequestration Well #2 (WVCCS2). The injection period is expected to last 12 years and inject 20 million metric tons of CO_2.

At this site, the Bainbridge or Salina group, known to as the Silurian, with a formation top at ~ 2,000 ft MD (~1,400 ft TVDss), is considered to be the lowermost USDW.

The injection zone was swabbed in the Wabash #1 stratigraphic test well. The resulting fluid sample was analyzed at 34,250 mg/l Total dissolved solids (TDS), and is therefore not a USDW.

Site Characterization

Regional Geology, Hydrogeology, and Local Structural Geology [40 CFR 146.82(a)(3)(vi)]

Injection Zone

Potosi Dolomite

The Potosi Dolomite is a relatively pure dolomite unit that underlies a large area of Indiana and Southern Illinois. On pg. 4 of the Narrative, it is stated that the Potosi Dolomite (injection zone) is "the basal unit of the Knox Supergroup in Indiana or Knox Group as it is referred to in Illinois." However, the stratigraphic column in Figure 1 of the narrative shows that the Potosi Dolomite is the basal unit of the Knox Supergroup in Indiana but it is not the Basal unit of the Knox group in Illinois. The Potosi Dolomite is 689 ft thick at the site of Wabash #1 and thickness ranges from 100 ft in northern Illinois to 1,500 ft in southern Indiana. The Potosi in Indiana comprises of the indistinguishable dolomitic upper Franconia, Potosi, and Eminence units.

Confining Zones

The permit application narrative describes three layers that provide confinement to varying degrees: the Shakopee and Oneota Dolomites, which immediately overlie the Potosi Dolomite injection zone; the Dutchtown Formation, Platteville Group, and Joachim Dolomite, which are argillaceous carbonate rocks with embedded shale intervals; and the Maquoketa Group, which is considered to be the primary seal for the project.

Shakopee Dolomite

The Shakopee and Oneota Dolomites are the 2 formations immediately overlying the Potosi Dolomite. Both are described as dense, fine to coarse crystalline formations with chert nodules (Narrative pg. 4). The Shakopee formation is 616 ft thick at the Wabash #1 well, divided into the upper Shakopee Dolomite (346 ft) and lower Shakopee Dolomite (270 ft) in Table 1 of the AoR CA (pg. 7).[1] The upper Shakopee contains 101 ft of shale and the lower Shakopee contains 71 ft of shale. The Oneota Dolomite is 408 ft thick and contains 15 ft of shale. It is stated that the Shakopee ranges from its "eroded limit in northern Indiana to an estimated 2,000 ft in southwestern Indiana" and ranges from, "50-150 ft in northern Illinois increasing in thickness to over 2,500 ft near the southern extent of Illinois. The "eroded limit" of the Shakopee was caused by erosion at the post-Knox unconformity. The Shakopee is located between 3,354 ft MD and its base at 3,970 ft MD at the Wabash #1 well (Narrative pg. 5). An Isopach map is provided for the Shakopee formation in Figure 5.

Questions for WCS:

- Is there a reason why the shales of the Oneonta, St. Peter Sandstone, Platteville, and Trenton Limestone are not discussed in more detail as confining units despite being included in the cumulative total for the shale thickness as evidence of confinement? Will these formations contribute to confinement?

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[1] Throughout this document, references are made to the two applicant submittals reviewed: the 146.82A permit application narrative ("Narrative"), and the AoR and corrective action plan ("AoR CA").

- Please comment on the integrity of thinner shales (in the Oneonta, St. Peter Sandstone, Platteville, and Trenton Limestone) as confining features.
- Please label the isopach lines in Figure 5.
- While a higher gamma ray signature is characteristic of the Shakopee and Oneota, most likely reflecting clay content, the density and density-porosity curves in Figures 2 and 3 show porous intervals in these formations as well (e.g., Huisinga well). Please explain how these formations will act as a confining layer if they possess heterogeneity typical of a carbonate and arguably as much porosity as the Potosi based on the logs in Figures 2 and 3.
- The application describes the Eau Claire Shale as the bottom confining unit. What information has been or will be gathered to characterize this formation?

Dutchtown Formation

The Dutchtown Formation, Platteville Group, and Joachim Dolomite are argillaceous carbonate rocks with embedded shale intervals. The thickest of these shale intervals is in the Dutchtown Limestone at 70.5 ft, followed by the Platteville group shale (16 ft). It is unclear if the Joachim Dolomite has shale interval. The Dutchtown formation has a thickness of 150 ft – 200 ft based on drilling operations in the Cape Girardeau area and cited research. It is stated that the thickness of the Dutchtown formation is "over 75 ft thick and based on the mod log, 30% shale is present in well cuttings samples." However, according to the Table 1 of the AoR CA (pg. 7) the formation thickness is listed as 84 ft at the Wabash #1 well. It is noted that clay content in the carbonate layers may have caused high gamma ray and lower neutron signatures (pg. 5). Isopach maps for the confining for the Dutchtown Formation were not provided. Figures 2 and 3 present log data from wells surrounding the proposed injection site for the Dutchtown formation.

Questions for WCS:

- Please clarify whether the Joachim Dolomite is intended to be a confining layer.
- Please update the Narrative to reflect the current understanding of formation thicknesses or provide comment on the accuracy of provided estimates.
- If available, please include an isopach map of the Dutchtown Formation.
- A higher neutron porosity signature is typically indicative of higher clay content. Please support the statement on page 5 that a higher neutron porosity reflects a lower clay content, or revise this statement.
- The log character of the Dutchtown Formation looks highly variable in Figures 2 and 3. Please explain how this heterogeneity is considered in the characterization of the Dutchtown for confinement.

Maquoketa Group

The Maquoketa Group is made of Upper Ordovician Shale units and is the primary seal in the Illinois basin and for the proposed Class VI project. Figure 6 shows a structural map of the top of the Maquoketa Group (AoR CA pg. 11), but there is no isopach map of the Maquoketa Group. The Maquoketa Group unconformably overlies the Trenton Limestone in Indiana and is laterally extensive in the Illinois basin (AoR CA pg. 5). It is stated that the Maquoketa group has been eroded in northern Illinois. The Maquoketa shale is overlain by the Silurian, where the lowermost USDW is reportedly located.

Questions for WCS:

- Please include a structure map of the Potosi Dolomite.
- Please provide an isopach map of the Maquoketa shale.
- The Maquoketa Shale is listed as (~312 ft), 314 ft, and 315 ft in different sections of the Narrative and the AoR and Corrective Action Plan. Please update the estimates of the thickness of the Maquoketa for consistency.

Geologic History

According to Kolata and Nelson (1990), the Illinois Basin was formed in the Late Cambrian over the northeast extension of the Reelfoot Rift system. The Illinois Basin is bordered by prominent structures. Rates of subsidence during the late Cambrian were greatest in the Rough Creek Graben, where the Illinois Basin reaches its maximum depth of 30,000 ft. Cambrian seas left widespread and thick deposits of mostly coastal and nearshore shallow marine sand.

The Knox carbonates are part of the Great American Carbonate Bank found throughout North America and formed during the Cambrian and Ordovician. The Potosi Dolomite consists of relics of bioclasts, ooids, peloids, indicating a shallow marine depositional environment. Cambrian to Permian formations are typically marine carbonates with lesser amounts of shale, sandstone, siltstone. This section of the Narrative also describes the seismic history of the region; see additional discussion under "Seismic History" below.

Question for WCS:

- Please provide a clearer legend for Figure 38 and denote the WVCCS1 & WVCCS2 wells on the figure.

Geologic Features

It is stated that there are, "no known structural features that would negatively impact the proposed injection site." The closest large geologic feature to the proposed injection site is the Lasalle Anticlinorium, located 20 miles away, marked in Figure 8 (Narrative pg. 12). The only resolvable faults in the AOR are in the Precambrian and lower Mt. Simon Sandstone," shown on the Wabash 2000 seismic reflection data in Figure 13 (Narrative pgs. 6,17, and 20). Otherwise, the closest regional fault is the Mt. Carmel fault in south-central Indiana, 50 miles southeast from the proposed injection site.

Question for WCS:

- Please provide depths for the seismic reflection profiles in Figures 11, 13, and 14.

Maps and Cross Sections of the AoR [40 CFR 146.82(a)(2), 146.82(a)(3)(i)]

Each injection well has an associated AoR which is dictated by the migration extent of the CO_2 plume at each well. Figure 9 represents the areal extent of the CO_2 plumes/AORs. Included in Figure 9 are: two injection wells (WVCCS1 & WVCCS2); two confining layer monitoring wells (CM1 & CM2); and the location of the in-formation monitoring wells (FM1 & FM2). All pre-existing wells or artificial penetrations (oil, gas, & water wells) within the 2 AoRs have been identified and are summarized in Table 1. 61 total artificial penetrations exist, of which none penetrate the primary confining layer within

4 miles of either injection well. See the evaluation of the AoR and Corrective Action Plan for additional discussion and questions.

Question for WCS:

- Figure 9 does not show 61 artificial penetrations within both AORs. Please revise the figure to include all wells. If the wells are located on top of each other due to scale, no revision is needed.

Faults and Fractures [40 CFR 146.82(a)(3)(ii)]

Evidence for Faults and Fractures

Based on three 2D seismic reflection profiles, “the only resolvable faults in the AOR are in the Precambrian and lower Mt. Simon Sandstone,” shown on the Wabash 2000 line (pg. 17 Narrative). Sonic and density wireline logs were correlated with the results of seismic well reflection analysis using synthetic seismographs.

It is stated that faults in the confining formations (Maquoketa to Oneonta) are “irregular to isolated fractures with no distinct indication of interconnectedness” (Pg. 5 AoR CA) based on logs of the stratigraphic test well and seismic analysis of the site. However, there is no seismic reflection data for the Potosi Dolomite because, “the 20-ft thick, porous Potosi reservoir interval was not resolvable on the seismic data collected.” The application therefore concluded that the lack of seismic reflection data for the Potosi Dolomite does not present an issue because there are no known faults in the Potosi Dolomite or the immediately overlying or underlying strata (Narrative pg. 17); however it is noted that there are irregular and isolated fractures located in the Potosi.

Formation Micro Imager log data from Wabash #1 were used to reveal small-scale fractures from the Maquoketa to the Oneonta. The wireline did not extend into the Potosi Dolomite, and thus results for the fractures in the Potosi Dolomite are unavailable. There were no fractures identified in the upper half of the Maquoketa Shale and there were small (6 in. or less) fractures that are “commonly not connected and occur 1 to 2 ft apart vertically” in the lower half (Narrative pg. 17).

Although nearly all the fractures analyzed in core taken from the Wabash #1 well for the Maquoketa Group showed marks consistent with drilling or handling marks, a few fractures, “do not show drilling induced fracture patterns…and can extend several feet” (Narrative pg. 18).

Impact of Faults and Fractures on Containment

The application states that, based on the above assessment of faults and fractures in the region, there are no faults in the Potosi Dolomite that would negatively impact containment. It further states that, “Fracturing in strata above the Potosi Dolomite is present in some beds as isolated or irregular features without any indication of interconnectedness” (Narrative pg. 18). The application also states that multiple beds above the Potosi Dolomite do not have fracturing for over 100 ft, but it is not immediately clear where these beds are located stratigraphically.

Tectonic Stability

The termination of faults in the Mt. Simon Sandstone, lateral continuity, and consistency of formation thicknesses throughout the AoR is used as proof of tectonic stability in the region. Furthermore, differences in salinity of “hydrostratigraphic units” were used as evidence that there is no cross-formational fluid migration.

Questions for WCS:

- While it is understood that fractures are “commonly not connected,” the frequency and size of connected fractures remains unclear. Please provide more detailed comment on the frequency of connected fractures and what criteria were used to distinguish “connected” fractures from singular large fractures.
- Please provide detail on the depths of intervals with no fracturing and explain the methods by which this determination was made for each such bed.
- Please provide more detail on the salinities of the units tested to support the statement on page 18 that, “differences in salinity of hydrostratigraphic units were used as evidence that there is no cross-formational fluid migration.”

Injection and Confining Zone Details [40 CFR 146.82(a)(3)(iii)]

Depth, areal extent, and thickness of the injection and confining zones

As detailed in Table 4 of the Narrative, the Maquoketa Group (primary seal) has a thickness of 314 ft with a shale thickness of 312 ft, and its depth at the Wabash #1 well is 2,386-2,700. The Potosi Dolomite is 784 ft thick and its depth at the Wabash #1 well is 4,378 ft. The other “confining zones” (Oneota Dolomite – Trenton Limestone) each contain varying amounts of shale intervals. These intervals range in thickness from 3.5 – 101 ft.

Although all of these shales are reported to have sealing characteristics, it is stated that the thicker shale intervals, “are considered the most effective seals within this package because these shales are more ductile, have less tendency to fracture and have extremely low vertical permeabilities.” (Narrative pg. 21) Thicknesses and depths were determined through wireline logs at Wabash #1 well in conjunction with geological research. Available regional geologic information was used to establish that the injection zone and confining zone extend well beyond the AoR.

Variability in thickness of the injection and confining zones within the AoR

Figures 16 and 17 show logs from wells around the Wabash #1 well forming cross sections through the AoR in the southwest-northeast and south-north directions (pgs. 29 and 30). The logs support the applicant’s finding that the injection zone is laterally extensive but do not include the Maquoketa Group.

Question for WCS:

- Please update Figures 16 and 17 to show the Maquoketa Group.

Injection and confining zone properties

Petrophysical analyses of geophysical logs from Wabash #1 were used to determine the properties of the injection and confining zones (pg. 22). It is stated that a, “detailed suite of geophysical logs collected in this well permit a continuous evaluation of mineralogical, lithological, and petrophysical characteristics across the injection formation and confining zones.”

According to Table 5 of the Pre-Operational Testing Plan, logging as part of long string open hole testing (e.g., natural gamma ray spectroscopy, elemental spectroscopy, formation micro imager, magnetic resonance, dipole sonic, and quantitative ELAN) and vertical seismic profiling will be used to enhanced the characterization of the geologic and geomechanical properties, injectivity, and confinement.

It is also stated that there are core samples and rock cuttings available for the Maquoketa Group (Narrative Pg. 22). No cores have been taken within the Potosi Dolomite; however, the Pre-Operational Testing Plan indicates that, during drilling operations whole core samples of the formation will be collected between about 4,500 and 4,700 ft.

Potosi Dolomite well testing and permeability estimation

WCS included identical/similar discussion concerning Potosi Dolomite Well Testing in the AoR CA Narrative; please see the report on the AoR and Corrective Action Plan for discussions and questions.

Mineralogy and petrology of the injection and confining zones

Wabash #1 Petrophysical Analysis

WCS used measurements of bulk density, neutron porosity, photo electric and acoustic time to estimate matrix density and total porosity (Narrative pg. 23). Lithology and ranges for porosity were estimated using neutron-density, Pe-density, and M-N cross plots.

Potosi Dolomite at the proposed injection interval

WCS included identical/similar discussion concerning Potosi Dolomite Well Testing in the AoR CA Narrative; please also see the report on the AoR and Corrective Action Plan for discussion.

Questions for WCS:

- On Figure 19, there is no caliper log in the first track with the gamma ray. The PE and NPHI log curves are nearly off-scale, leading to the conclusion that the hole might be washed-out in the tested interval. Can the porosity estimation for this interval be supported by additional well data?
- What matrix density was used for the DPHI and NPHI log curves?
- Please include a caliper, resistivity, and density log in Figures 15, 19, 21, 23, 26, 28, 30, and 33.

Overlying and Confining Units

WCS included identical/similar discussion concerning Potosi Dolomite Well Testing in the AoR CA Narrative; please see the report on the AoR and Corrective Action Plan for discussions and questions.

Questions for WCS:

- Please identify the geophysical logs that will be used for continuous evaluation of the injection zone and confining zones. These logs, their target formations, and the site characterization objectives, should be described in the pre-operational testing plan.
- Have the petrophysical analyses been calibrated to cores from the Maquoketa Group?
    - If not, what uncertainty is there regarding the results of the petrophysical analyses and formation characteristics? Please discuss pre-operational testing plans regarding petrophysical calibration.
    - If so, which cores from which wells were used for calibration?

Geochemical reactions

WCS states that the proposed CO_2 injectate will be more than 99% pure after compression and dehydration (Narrative pg. 24). Previous analyses within the Knox Group revealed dissolution of Dolomite with exposure to supercritical CO_2 and brine. Analysis of post reaction brine from the Maquoketa Group showed elevated amounts of aluminum, barium, calcium, potassium, magnesium, sulfur, silicon, and strontium. These elevated levels are indications of dissolution of feldspar, clay, carbonate, and sulfide minerals. There was observation of K-feldspar altering to kaolinite or quartz, however this alteration is not expected to impact the sealing capacity of the Maquoketa group substantially.

Modeled dissolution of carbonate minerals resulted in a 2.2% decrease in mineral volume, however it is believed that this decrease would be less given actual injection because, “the lower water-to-mineral ratio” is a “limiting factor to carbonate dissolution.” (Narrative pg. 24)

Question for WCS:

- Why wasn’t a more accurate water-to-mineral ratio used to model dissolution?

Average, and spatial distribution, of porosity and permeability values within the injection and confining zones

Tables 4 and 5 of summarize the porosity and permeability of each zone. Discussion of those tables is presented in the AoR CA report. WCS states that the spatial distribution of the confining zones and injection zone is assumed to be relatively uniform within the AoR, but confirmation of this assertion is constrained by a lack of available data.

Estimated storage capacity and injectivity of the injection zone, and integrity of the confining zone

The applicant proposes to inject 1.67 million metric tons of CO_2 per year for a period of 12 years, totaling 20.4 million metric tons (Narrative pg. 2). However, on Narrative pg. 3, it is stated that injection will “result in the successful sequestration of 20 million metric tons of CO_2.” Furthermore, simulation used injection rates of 834,390 metric tons per year for each well over a 12 year period for a total of 20.02 million metric tons (Narrative pg. 25). This information is consistent with information presented in the AoR and Corrective Action Plan.

The application notes that additional information necessary for the characterization of the Maquoketa, the injection zone, and the formations immediately overlying the injection zone will be gathered in pre-operational testing, including wireline logs, in-situ testing and full core samples (Narrative pg. 25). Other pre-operational testing activities include whole cores for the Maquoketa, Shakopee, and Potosi, and the tests summarized in Tables 2 and 3. Tables 2 and 3 are comprehensive and correspond to other documents in the GSDT, including the Pre-Operational Testing Plan.

Please see the discussion of “faults and fractures” above for additional discussion of confining zone integrity.

Geo-mechanical and Petrophysical Information [40 CFR 146.82(a)(3)(iv)]

Methods used to determine the geo-mechanical and petrophysical characteristics of the confining zone

WCS used measurements of bulk density, neutron porosity, photo electric and acoustic time to estimate matrix density and total porosity (Narrative pg. 23). Lithology and ranges for porosity were estimated using neutron-density, Pe-density, and M-N cross plots. A gamma ray log was used to identify clay and shale rich units, shown in (Figure 34). While the full thickness of the Maquoketa Group Shale is clearly distinguishable, the continuity of other thick shales such as the Dutchtown Shale are less resolvable. However, as discussed above in the estimated storage capacity section, the geophysical properties of the confining zone units will be further enumerated with pre-operational testing. FMI data and caliper logs were used for assessment of formation integrity, potential for drilling induced tensile fractures (DITFs), and wellbore breakouts (WBOs).

Geomechanical testing was performed on wax-preserved core samples obtained from the Wabash #1 well for the Maquoketa Group. A 61 foot, 3 ½ inch diameter, core was taken at the Wabash #1 well from depths 2,435 – 2,496 ft, well within the Maquoketa Group (2,385 to 2,700). Table 7 presents a summary of the preserved cores which includes 2 feet of wax core from the above-mentioned depth. Cores underwent triaxial compressive testing with confining pressures of 675, 1350, and 2025 psi with results interpreted based on Mohr-Coulomb failure at Schlumberger's Reservoir Laboratory (SRL).

Questions for WCS:

- As mentioned above in Injection and confining zone properties, please clarify if these petrophysical analyses are calibrated to core. If not, please discuss pre-operational testing plans regarding petrophysical calibration.
- How representative were the wax core samples and resulting geomechanical properties of the entire Maquoketa Group confining layer?

Identification of fractures

A computer tomography scan revealed breaks in a 2 ft section of Maquoketa Group whole core, with evidence of "isolated vertical and horizontal fractures." WCS states that, "these fractures are likely drilling- or handling-induced," however fractures that do not appear to be drilling or handling induced are discussed above in the Faults and Fractures section (Narrative pg.46). FMI logs revealed isolated fractures in the Shakopee Dolomite. Fractures in the upper Shakopee are short and terminate within individual beds, interspersed with relatively thick non-fractured beds. Fractures are more common in the lower Shakopee and have been observed crossing multiple beds. Fractures in the Dutchtown formation are localized and separated by unfractured intervals that can exceed 100 ft in thickness. WCS states that in the Maquoketa Group there were no "significant natural fractures" (Narrative Pg. 46); however, it is also stated (on Narrative pg. 17) that the Maquoketa Group has some fractures that were interpreted as conductive or open.

Questions for WCS:

- Please comment on the size of these bed crossing fractures in the Shakopee Dolomite.

- What criteria were used to determine which natural fractures are “significant” for purposes of confinement?

Rock strength of the confining zone

Uniaxial strength of ~26,000 psi determined based on the triaxial testing of 5 cores from the Maquoketa Group by extrapolating the uniaxial strength from the best fit line of the relationship between the compression strengths (675, 1350, and 2025 psi) and the resulting yield strength. WCS employed the methodology presented by Zoback (2007) of using the slope of the best fit line to estimate a coefficient of internal friction (.58), angle of internal friction (30^o), and cohesive or shear strength (~7,514 psi or ~52 MPa) (Narrative pg. 46). Compressional velocity, shear velocity, dynamic and static young’s modulus, and dynamic and static Poisson’s ratio are summarized in Table 9. The Narrative states that testing of cores from other formations will be completed during pre-operational testing; this is also described in the Pre-Operational Testing Plan.

In-situ stress field of the confining zone

Observation of DITFs and WBOs in the logged interval at the Wabash #1 well show that the maximum horizontal stress trends W-E (in Figure 36) and that the minimum horizontal stress is perpendicular to this direction. Figure 37 shows the estimated dynamic elastic properties and in situ stresses recorded in log data. WCS concludes based on Figure 37 that this is likely a strike slip stress regime.

Question for WCS:

- Due to the likely strike-slip stress regime, faults may not be resolvable on 2D or 3D seismic. If this is the case, what seismic data will be collected to address this as part of pre-operational testing?

Average pore pressure of the confining zone

The average hydrostatic pore pressure of the confining zones is estimated to be 0.43 psi/ft.

Question for WCS:

- Please clarify the source of the estimate of hydrostatic pore pressure on page 47 of the Narrative.

Anomalies or uncertainties in the data

In comparison to core from the Illinois Basin-Decatur Project (IBDP), the uniaxial compressive strength (UCS) value of ~26,000 appears high. Table 9 summarizes uncertainty in UCS values by presenting the data as a range of values (Narrative pg. 48). This uncertainty may be due to sedimentary features present in the rock but was addressed by testing cores in three different orientations.

Question for WCS:

- Other than data from the IBDP, were cores available for comparison from other locations?

Seismic History [40 CFR 146.82(a)(3)(v)]

It is stated that the seismic activity is infrequent based on data in Table 10 (Narrative Pg. 52) and Table 11 (Narrative Pg. 52 – 54), which show the earthquake history in Indiana and Illinois respectively. Figure 38 (Narrative Pg. 56) shows a map of Indiana's faults and historic earthquakes (Indiana Geological Survey). Table 10 provides the locations of all (44) magnitude 3 or greater earthquakes in Indiana from 1817-2012 (Indiana Geological Survey) and functions as a key to the earthquakes shown in Figure 38. Table 11 contains the results of a query in USGS records for all earthquakes greater than 2.5 intensity in Illinois and Indiana for the past 20 years, for a total of 80. Cross reference of the 2 tables shows that some of the earthquakes noted in Table 10 that should be included in Table 11 are not included. In particular, the January 26th, 2012 3.0 magnitude and the June 18th, 2002 4.4 magnitude should be included. Seismic history increases in southern Indiana and Illinois towards multiple seismic zones. It also seems that the Figure 38 may be missing Map ID #40, which correlates to the June 18th, 2002 4.4 magnitude earthquake.

Questions for WCS:

- Please provide a clearer legend for Figure 38 and add Map ID #40 to the map. Were 2.5 magnitude earthquakes in Indiana considered?
- Is there a reason that certain earthquakes may have been excluded from the list generated for Table 11?
- The application, on page 58 states, that the "relative risk of the site is considered minimal." Please clarify how the seismic risk profile for the site will be quantified. Specifically, EPA recommends that the evaluation address how the project: has a geologic system free of known faults and fractures and capable of receiving and containing the volumes of CO_2 proposed to be injected; will be operated and monitored in a manner that will limit risk of endangerment to USDWs, including risks associated with induced seismic events; will be operated and monitored in a way that in the unlikely event of an induced event, risks will be quickly addressed and mitigated; and poses a low risk of inducing a felt seismic event. EPA: we included this question because other Class VI permits included a discussion of how the project will not contribute to induced seismicity. The items in this question relate to specific parts of an evaluation that is included in the ADM administrative record. If you would like something similar for Wabash (and this information isn't elsewhere in the application files), we suggest requesting a brief write up.

Hydrologic and Hydrogeologic Information [40 CFR 146.82(a)(3)(vi), 146.82(a)(5)]

Map of wells and other listed features

Figure 9 presents a map of the AoR and all wells, subsurface sites, surface water, and other relevant features (Narrative pg. 16). Discussion of this figure is presented above under "Maps and Cross Sections."

Unconsolidated Aquifers

The primary source of drinking water in west central Indiana are unconsolidated aquifers, with the most significant being the Middle Wabash River Basin, consisting of unconsolidated surficial and buried sand and gravel. The Coal Mine Spoils Aquifer System covers 5-7% of the Vigo and Vermillion counties. It is stated that high iron content and pH less than 7 can severely limit potential groundwater use (Narrative pg. 59), however it is unclear if this water is currently used as drinking water or could be used as drinking water. Figure 41 maps the unconsolidated aquifer system of Vermillion County and Vigo County in Indiana. There is no map of the unconsolidated aquifers present in Illinois.

Question for WCS:

- Please provide a map of the unconsolidated aquifers present in relevant counties in Illinois.

Unconsolidated deposits range in thickness from 50 to 100 feet and generally thicken in the north and northeast direction of Indiana, as shown in Figure 42. Although Figures 41 and 42 are difficult to interpret due to low resolution, links to the data sources provide digital downloads with resolvable resolutions.

Bedrock Aquifers

Within the Middle Wabash River Basin, there are three bedrock aquifers located in the McLeansboro Group of the Pennsylvanian system (the primary bedrock aquifer), the Mississippian, and the Silurian-Devonian carbonate rocks (Figures 43 and 44; Narrative pg. 65-66). The Pennsylvanian system deposits and unconsolidated deposits are ~750 ft thick at the Wabash #1 well. Detailed information about the groups within the Pennsylvanian system is summarized on Narrative pg. 60 and in Figure 43, including thicknesses, static water level, and comments on production. Figure 44 shows cross sections of the Middle Wabash River Basin through the Vigo and Clay counties and Vermillion and Parke Counties.

Although Figure 43 is difficult to interpret due to low resolution, a link to the data source for Figure 43 provides digital downloads with resolvable resolutions.

The Mississippian carbonates beneath the Pennsylvanian are high producing due to enhanced permeability caused by the development of solution channels (Palmer, 1991). These carbonates are ~1,000 ft thick.

The Silurian-Devonian carbonate rock is not a significant producer but is an important groundwater source and is noted as the lowermost USDW (Narrative pg. 60). Overlying this sequence is the 100 ft thick New Albany Shale and underlying it is the ~314 ft thick Ordovician Maquoketa Group (primary seal).

Questions for WCS:

- Is there a reason to believe that the reactions documented by Palmer (1991) that form solution channels in the Mississippian carbonates will not significantly impact formation permeability of confining zones?
- How did this information inform the interpretation of model dissolution which estimated a 2.2% decrease in mineral volume?

Regional Groundwater Flow

Based on available literature cited in the application, groundwater flows toward the center of the Illinois Basin from the outer regions of the basin, specifically in the Ordovician St. Peter Sandstone and carbonate rocks of the Silurian-Devonian and Mississippian formations. Groundwater flow direction in the AoR is generally eastward.

Potentiometric surface maps of bedrock aquifers provided by the Indiana Department of Natural Resources use static water level measurements collected from available well data. There is no clear reference explaining which map is referred to; however, it appears to refer to Figure 45.

WCS provided a contour map showing the 10,000 mg/L TDS boundary for the Silurian-Devonian carbonate aquifer systems (Schnoebelen et al. 1998; Figure 46). The application states on page 3 that the Bainbridge or Salina Group, known to as the Silurian, with a formation top at ~ 2,000 ft MD (~1,400 ft TVDss), is considered to be the lowermost USDW. However, no information is provided on the TDS content of the Silurian, or how this was determined to be the lowest USDW in the AoR.

WCS states that the St. Peter Sandstone is not expected to be a USDW "in Southwestern Vermillion and Northwestern Vigo Counties" based on conversions of chloride concentrations of two brine samples from wells in Clark County Illinois using equations provided developed by Panno et al. (2018), using the following equations:

$$\text{Eq. 9} \qquad < 5000\ mg/L:\ Cl^{-} = 0.0022 \times TDS^{1.5328} \qquad (R^{2} = 0.895)$$

$$\text{Eq. 10} \qquad \geq 5000\ mg/L:\ Cl^{-} = 0.637 \times TDS \qquad (R^{2} = 0.989)$$

Results of this calculation showed that the TDS content of the two samples were 20,800 and 125,000 mg/L TDS. The TDS of the fluid in the Potosi Dolomite was analyzed to be 34,350 mg/L (Narrative pg. 61).

Questions for WCS:

- Please provide information about the TDS content of the Silurian, including the source of the value, and any pre-operational testing that is planned to confirm this and provide the baseline data required at 40 CFR 146.82(a)(6).
- In addition to average water well depth referenced on page 80, please explain how USDWs were identified in the AoR.
- Please provide a stratigraphic column that shows the formation that contains the lowermost USDW (Bainbridge/Salina/Silurian).
- Which equation was used for the calculations in equations 9 and 10?
- Considering the formulas are intended to determine Cl$^-$ concentrations based on known TDS content, and known TDS is necessary in determining the appropriate equation, why is this considered to be an appropriate method of estimating TDS?
- Is the St. Peter Sandstone expected to be or currently used as a USDW outside of the Vermillion and Vigo Counties?
- Please update the legend in Figure 46 for clarity.

Geochemistry [40 CFR 146.82(a)(6)]

Data Sources, Samples, and Analyses

Fluid samples were collected from Wabash #1 for the Potosi Dolomite well test interval from 4,505 ft to 4,525 ft. 24 swab runs were completed prior to collection of the final swab sample which was analyzed at the Illinois State Water Survey Analytical Laboratory (Narrative Table 2 pg. 71).

Analyses included Ion Chromatography and Inductively Coupled Plasma-atomic Emission Spectrometry (ICP-ES) to determine major, minor, and trace element composition. Results of this analysis show that the Potosi fluid had TDS of 34,250 mg/L. Other data and sources used for geochemical analysis include rock cuttings, full diameter core, sidewall core, and geophysical logs (density, photoelectric index, conductivity, and spectral gamma ray).

Questions for WCS:

- Please clarify the relevance of the logs in Table 2 to this section.
- The application stated that full diameter core and sidewall core were not collected over all intervals. Please update the section to state the intervals that did not have available core data.
- WCS also states that there is, "considerable regional understanding of the geochemistry of fluids and rock lithology within the Illinois Basin. (Narrative pg. 71)" Please provide citations or descriptions of the geochemistry of intervals where core data was unavailable.
- The discussion of pre-operational testing in the narrative indicates that no coring will be performed at WVCCS2 given its proximity to core collection sites. Given that the reservoir is most likely a highly heterogeneous carbonate, please consider collecting at least RSWC's at WVCCS2 to calibrate petrophysical calculations and reduce overall uncertainty.

Solid-Phase Geochemistry

General descriptions of the characteristics of the Injection and Confining Zones are presented in the "Injection and Confining Zone" section and are discussed above.

Results of X-Ray diffraction (XRD) analyses from the Cabot No. 3 well in Tuscola, IL showed that the Oneota Dolomite averaged 68.3% carbonate material, 2.0% clays, and 30.3% other minerals, while the Shakopee Dolomite averaged 84.4% carbonate material, 3.7% clays and 12.7% other minerals. Carbonate material was over 95% dolomite, clay was primarily illite, and the other minerals observed in significant amounts include quartz, feldspar, pyrite, and ankerite (Texas World Operation, 1995).

Cross plots of neutron density in combination with gamma ray logs show that the Dutchtown formation is a mixture of shale and shaly carbonates. These logs are shown in Figures 2 and 3, and discussion is presented above in Dutchtown Formation section under "Confining Zones."

Litho-scanner log analysis in the Wabash #1 well for the Trenton Limestone and Black River Group identified predominantly calcite (~70%) and dolomite (~20%) with minor amounts of quartz, feldspars, and clay minerals. A study by Medina et al. (2020) analyzed a sample from the Trenton Limestone consisting of 98% calcite with trace amounts of dolomite, quartz, albite, and illite.

The Maquoketa Group is heterogenous, consisting of clastics and carbonates. A study by Medina et al. (2020) found that there were 5 predominate lithofacies within the group: high calcite (limestone), high clay content (silty clay), high clay content and carbonate-rich intervals (calcareous/dolomitic shale); high calcite and moderate clay content (muddy limestone), and high clay (shale) (Narrative pg. 71). XRD analyses from a well in White County, IL indicate that quartz and illite are the primary minerals in the Maquoketa Group. Other minerals include calcite (primarily at the base of the Maquoketa), dolomite (decreasing with depth), chlorite, albite, rutile, microcline, and pyrite. The latter 5 minerals make up less than 10% of the formation content (Narrative pg. 71-72).

Questions for WCS:

- Is XRD data available for any other formations than the Oneota Dolomite and Shakopee Dolomite?
- If not, are there plans to perform this (or similar) analysis of the injection and confining zones during pre-operational testing?
- Please fix the typo on page 71 saying, "Medina el at. (2020)."

Geochemical Data and Modeling

Based on experimental reaction and modeling information for the Potosi Dolomite and Maquoketa Group obtained from ISGS studies and reports on cores from wells in Missouri and Illinois, in addition to model results, WCS concludes that, "CO_2 is expected to have negligible to no reaction with the minerals in the Maquoketa Group (Narrative pg. 72)."

The application describes core flood experiments that were conducted to identify the reaction mechanisms, kinetics and solid-phase products likely to occur when exposed to supercritical CO_2. SEM analysis of Knox Group Dolomites revealed dissolution yielding 12-47% reduction in volume. Post-reaction brine analysis Knox Group dolomites showed elevated concentrations of calcium, magnesium, strontium, and barium, indicating dolomite dissolution. Post-reaction brine analysis also revealed that solution equilibrium was reached before the end of the 4-month experimental period, indicating that dissolution is most likely to occur in early stages of injection. Equilibrium was corroborated with short-term (6-hour) core flood experiments.

Batch reactor experiments were conducted on samples from the Potosi Dolomite (southwest Missouri outcrop) and Maquoketa Group (IBDP site core). Yoksoulian et al. (2014) compared post-reaction brine chemistry results for the Potosi and Maquoketa to USEPA drinking water standards and found that concentrations were, "generally less than the USEPA MCLs and in some cases results were inconclusive because analytical method detection limits were up to 150 times greater than the USEPA MCLs. (Narrative pg. 73)" Post-batch reaction brines from the Maquoketa had elevated levels of aluminum, barium calcium, potassium, magnesium, sulfur, silicon, and strontium, indicating dissolution of feldspar, clay, carbonate, and sulfide minerals. Results of computational modeling of reactions in the Maquoketa Group and their impact on seal integrity are discussed below in the Site Suitability section.

Questions for WCS:

- Will cores from the Potosi Dolomite close to the proposed injection site be compared to the cores from southwest Missouri once they are available?
- Is there other information that can confirm that the outcrop is indicative of formation characteristics at the proposed injection site?

Geochemical Reactions and Mineral Trapping

WCS cited a study by Zhu et al. (2013) in which kinetic batch models were used to "simulate long-term chemical and physical interaction of formation rocks, brines, and pure CO_2 in the primarily dolomitic upper Knox in western Kentucky which is consistent with the mineralogy in the AoR (Narrative pg. 73)." Rock core, fluid samples, and geophysical log data was collected from a carbon storage test well used for the injection of 626 metric tons of CO_2 in the Knox Group interval, and used as inputs for modeling. Results showed dissolution of dolomite and precipitation of quartz and dawsonite.

Table 12 shows concentration ranges of selected analytes in swab sample taken from the Potosi Dolomite for Wabash #1 but is not explicitly referenced in the text. For predominately dolomitic permeable sections of the model, mineral trapping capacity for CO_2 was small.

Question for WCS:

- Please include references to Table 12 where applicable.

Site Suitability [40 CFR 146.83]

The application notes that proposed injection zone, the Potosi Dolomite, extends throughout most of Illinois and Indiana and ranges in thickness from 100 ft in northern Illinois to more than 1,500 ft in southernmost Indiana. The Potosi Dolomite injection zone is 689 ft thick and occurs at 4,473 ft MD in the Wabash #1 well. The predicted area required for CO_2 storage is much smaller than the areal extent of the proposed injection zone.

Permeability testing performed on the Wabash #1 well provided a permeability value of 2,400 mD across an injection unit within the Potosi Dolomite (24,000 mD-ft over 10 ft). This value was used for the dynamic modeling to capture the entire injection period. The application asserts that this modeling demonstrated that the injection zone is capable of accepting the entire proposed volume of CO_2 that will be injected for the duration of the project. Additionally, secondary permeability testing of the injection interval revealed higher permeabilities, up to 45,000 mD, that exist within the Potosi Dolomite. The 2,400 mD permeability value was used to ensure that no limitation on injection capacity will be encountered.

The Maquoketa Group (the primary seal) is observed as 314 ft thick (2,386 to 2,700 ft MD) in the Wabash #1 well. It is composed of interbedded shale, argillaceous limestone, and dolomite. The shale intervals are considered to be the most effective seals within the Maquoketa Group because they have a ductile behavior, minimal fracture tendency, and low vertical permeabilities. The Maquoketa Group is found over the entire Illinois Basin and ranges in thickness from 100 ft in the west to greater than 800 ft in the east. Analysis of 2D seismic data revealed that no transmissive faults or fractures exist within the injection zone or any of the identified confinement layers. Regional mapping, informed by 2D seismic information, indicates that the identified confining layer is continuous across the AoR.

The 2D seismic lines (Line 1000 in Figure 11 and Line 2000 in Figure 13) attempt to correlate the Wabash #1 with the seismic reflection data. As the caption to Figure 11 notes, it is difficult to follow the different reflectors across the seismic profile. However, vertical seismic profiling is planned as part of pre-operational testing; any new information gathered about the transmissivity of faults or fractures should be incorporated into the evaluation of confining zone suitability.

No artificial penetrations of the primary confining layer exist within the expected AoR, as determined by a record survey for all oil, gas, and water wells in the AoR. The lack of artificial penetrations of the primary seal and transmissive faults and fractures ensures that no leakage pathways currently exist that threaten USDWs or could result in the release of CO_2 to atmosphere.

The CO_2 capture technology to be used produces a dry CO_2. Within the injection zone, the CO_2 and brine formation waters are expected to react with dolomite, resulting in some partial dissolution of the base material. This dissolution did not result in the precipitation of new solids during lab scale testing, therefore posing no risk of loss of porosity or permeability. The reaction between the CO_2, brine, and dolomite also reached equilibrium within the 4-month experimentation period, indicating the reaction was relatively short-lived in comparison to the injection time frame. Based on these observations, there are no adverse effects expected due to the interaction of the CO_2 with injection zone material.

Seal integrity was assessed through high-pressure, high-temperature batch reactor experiments conducted on samples from the Maquoketa Group. These experiments used either laboratory produced synthetic brine or deionized water to identify the reaction mechanisms, kinetics, and solid-phase products likely to occur when exposed to supercritical CO_2. After the batch reactor experiments were conducted, brines were sampled from the Maquoketa Group. They had elevated levels of aluminum, barium, calcium, potassium, magnesium, sulfur, silicon, and strontium indicative of feldspar, clay, carbonate, and sulfide mineral dissolution. Computational modeling projected no impact on seal integrity. The most significant observable reaction was alteration of K-feldspar to kaolinite and quartz which would not be expected to significantly impact seal porosity. Modeled dissolution of carbonate minerals estimated a 2.2% decrease in mineral volume at most with carbonate mineral dissolution projected to be less in an actual sequestration scenario due to the lower water-to-mineral ratio being a limiting factor to carbonate dissolution.

In addition to the Maquoketa Group primary seal, there are several distinct confining units that exist between the Maquoketa Group and the Potosi Dolomite injection zone. These formations, the Shakopee, the Dutchtown, and others, exhibit confining zone characteristics such as low porosity, interbedded shale layers and a lack of faults and fractures. While not considered the primary seal, they will act as restriction zones, greatly reducing the dependance on the Maquoketa Group. Based on model results, CO_2 is not expected to reach the Shakopee due to the low permeability of dolomite formations above the Potosi. The presence of these extensive restricting formations greatly improves the efficacy of the Maquoketa Group acting as the primary seal and ensures the LUSDW is protected.

Questions for WCS:

- Please describe the “early testing” referenced on page 75 that that took place resulting in a permeability of 2,400 mD and explain how this value is representative of the planned injection zone.
- Please clarify what is meant by the statement on page 75 that “The usage of the much lower value of 2,400 mD ensures that no limitation on injection capacity will be encountered.”
- During lab scale testing, were injection zone pressures and temperatures used? If not, are these expected to negatively affect the CO_2 – injection zone lithology interaction?
- Please clarify why carbonate mineral dissolution is expected to be less during injection operations than during modeled scenarios.
- Please clarify that any updated information about the transmissivity of faults or fractures gathered during pre-operational vertical seismic profiling should be incorporated into the evaluation of confining zone suitability.