Attachment 2: Area of Review and Corrective Action Plan
40 CFR 146.84(b)
Vervain Project, McLean County, Illinois
31 January 2023

Project Information

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Several figures contained within this document (AoR without CBI) contain Confidential Business Information (CBI) that is privileged and is exempt from public disclosure.

These images will be delivered to the EPA in a separate document (AoR with CBI). The figures listed below contain CBI and are redacted from the public disclosure version of this document:

CBI figures:
Figure 6: CBI: NV_INJ1 static model petrophysical prognosis
Figure 7: CBI: NV_INJ2 static model petrophysical prognosis

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List of Acronyms

2D	two-dimensional
3D	three-dimensional
ADM	Archer Daniels Midland Company
AoR	Area of Review
BHP	bottomhole pressure
CCS	Carbon Capture and Sequestration
CCS1	ADM Injection Well (drilled for the Illinois Basin–Decatur Project)
CH_4	methane
CMG	Computer Modeling Group
CO_2	carbon dioxide
EOS	Equation of State
EPSG	European Petroleum Survey Group
fbsl	feet below sea level
fbgl	feet below ground level
GEM	Generalized Equation Model
GRFS	Gaussian Random Function Simulation
H_2O	water
IBDP	Illinois Basin–Decatur Project
ISGS	Illinois State Geological Survey
kv/kh ratio	vertical permeability divided by horizontal permeability
KH	permeability-height product
kh	horizontal permeability
kv	vertical permeability
mD	millidarcy
MD	measured depth
mi^2	square miles
MIT	Mechanical Integrity Test
MNSM	Mt. Simon Formation
MSL	mean sea level
Mtpa	million tonnes per annum
NV_ACZ1	Vervain Above Confining Zone Monitoring Well #1
NV_ACZ2	Vervain Above Confining Zone Monitoring Well #2
NV_INJ1	Vervain Injection Well #1
NV_INJ2	Vervain Injection Well #2
NV_MA1	Mahomet Aquifer Monitoring Well #1
NV_MA1	Mahomet Aquifer Monitoring Well #2
NV_OBS1	Vervain Deep Observation Well
O&G	oil and gas
P&A	plugged and abandoned
PHIE	effective porosity
PNL	Pulsed Neutron Logging
PSI/FT	pounds per square inch per foot
PSIA	pounds per square inch absolute
Prog	well top prognosis
TDS	total dissolved solids

THP	Tubing head pressure
UIC	Underground Injection Control
USDW	Underground Source of Drinking Water

This document describes how geologic and hydrologic information were used to delineate the Vervain Project Area of Review (AoR). It also addresses the extent to which the Vervain Project needs to undertake corrective actions for features within the AoR that may penetrate the confining zone, and how such corrective actions will be taken if needed in the future.

Section 1.1 describes the computational model that was used to delineate the AoR. The description contains details regarding the computational model, the physical processes modeled, and the conceptual model and numerical implementation. It also describes the AoR, how the AoR will be re-evaluated over time, and the Vervain Project Corrective Action Plan. This document is intended to demonstrate compliance with 40 CFR 146.84.

1. Computational Modeling Approach (40 CFR 146.84(b)(1))

1.1. Model Background

Computational modeling of carbon dioxide (CO_2) injection into deep geologic formations requires the numerical simulation of complex, coupled hydrologic, chemical, geologic, and thermal processes that include multi-fluid flow and transport, partitioning of CO_2 into the aqueous phase, and chemical interactions with aqueous fluids and minerals. For the Vervain Project Site (Figure 1), a static geologic model was constructed with available subsurface data from the region, and the static model was then used as the framework for computational modeling. This section will discuss the static model generation and computational modeling results.

1.1.1. Static Model

The Vervain Project static model was developed using Rock Flow Dynamics' software tNavigator, which is a subsurface interpretation and geologic modeling program. Table 1 summarizes the workflow used to generate the static model; the model focuses on the Argenta Formation, Mt. Simon Arkose, Lower/Middle/Upper Mt. Simon Sandstone, Eau Claire Silt, and Eau Claire Formation. The workflow included:

- Interpretation of all publicly available well logs to generate structure and thickness maps,
- Petrophysical analyses of five select wells from the region (Figure 2; (Attachment 1:Project Narrative 2023),
- Generation of a static model for the total storage interval (Mt. Simon Arkose, Lower/Middle/Upper Mt. Simon Sandstone, Eau Claire Silt) and the Eau Claire Formation confining interval,
- Computational modeling of the CO_2 injection in the injection and storage zones, and
- Estimation of the maximum sustainable CO_2 injection rate, CO_2 plume size, and the area of the pressure front that defines the Vervain Project AoR.

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Figure 1: Vervain Project well locations. NV_INJ1 and NV_INJ2 are injection wells, NV ACZ1 and NV ACZ2 are above confining zone observation wells, NV_OBS1 is a deep observation well, and NV_MA1 and NV_MA2 are Mahomet Aquifer monitoring wells. Scale=4,000 feet.

Table 1: Summary of static and computational modeling steps

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Figure 2: Map showing the static model location and dimensions, the two Vervain Project injection wells (NV_INJ 1 and NV_INJ2), and the five wells used for petrophysical analysis.

Figure 3 and Figure 4 display horizontal and vertical perspectives of the model grid, and Table 2 summarizes the model layering, horizon type, and dimensions. The proportional static model layers in the Ironton-Galesville formations, the Eau Claire Formation, the Eau Claire Silt, the Upper/Middle/Lower Mt. Simon Sandstone, the Mt. Simon Arkose, and the Argenta Formation are relatively thin and were defined to capture vertical well log variability in the injection, storage, and confining zones that are the focus of the computational model. For instance, vertical grid sizes used in the Lower Mt. Simon and Arkose intervals were six feet and five feet, respectively. The formations above the Ironton-Galesville formations use one layer per zone, as the CO_2 is not predicted to migrate up to or penetrate the Eau Claire Formation seal (Table 2).

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Effective porosity and permeability logs derived from the petrophysical analysis of five nearby wells were upscaled to the model layers and distributed throughout the static model volume (Figure 2, Section 1.4, (Attachment 1:Project Narrative 2023)). Figure 5 displays the geologic prognosis of formation depths at the Vervain injection wells NV_INJ1 and NV_INJ2. The St. Peter Sandstone is the lowermost underground source of drinking water (USDW) (Figure 5).

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Figure 3: Map view of the static model area tartan grid showing horizontal grid size. Relatively smaller cells (400 x 400 feet) were used around the injection (NV_INJ1 and NV_INJ2) and observation wells (NV_OBS1). Cross section A-A' is shown in Figure 4.

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Figure 4: Static model cross section A-A' (Figure 3) showing horizontal and vertical cell dimensions. Vertical exaggeration=25x.

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Figure 5: Model zone cross section B-B' through the injection wells. The inset map in the upper right corner shows the B-B' orientation at the Vervain Project Site and is also shown in Figure 10. NV_INJ1 and NV_INJ2 = injection wells. NV_OBS1 is the observation well and projected onto the cross section, NV_ACZ1 and NV_ACZ2 are above confining zone observation wells, and NV_MA1 and NV_MA2 = Mahomet Aquifer monitoring wells. Vertical exaggeration=5x, ft=feet, and MNSM=Mt. Simon Sandstone.

1.1.2. Computational Model

The fluid flow model used for this application is Generalized Equation Model (GEM), a commercial simulator developed by Computer Modelling Group (CMG) of Calgary, Alberta. GEM has been developed by CMG primarily for modeling hydrocarbon reservoirs, and it is listed in the EPA document, "Rules and Tools Crosswalk: A Compendium of Computational Tools to Support Geologic Carbon Storage Environmentally Protective UIC Class VI Permitting" (Lackey, et al., 2022). This simulation software was selected because it has many advanced features for carbon sequestration modeling, including relative permeability hysteresis, CO_2 solubility in water, water vaporization, geochemistry, mineralization, thermal, and geomechanical properties.

For this application, an equation of state (EOS) was developed with three components: 1) CO_2, 2) methane (CH_4), and 3) water (H_2O). Since the static model was originally designed for hydrocarbon reservoirs, it requires a trace hydrocarbon component (CH_4). The following CO_2 trapping mechanisms are modeled: 1) structural, 2) residual trapped gas, 3) CO_2 dissolved in H_2O, 4) aqueous ions, and 5) mineralization.

The model uses well established, discretized, fluid flow equations and an adaptive-implicit method for solving the resulting sparse matrix (Collins, D.A.; Nghiem, L.X.; Li, Y.K.; Grabenstetter, J.E; May 1992), (Nghiem, L.X.; Li, Y.K.; September 4-8, 1989).

The model uses a cubic EOS with Peng-Robinson (PR) coefficients, and viscosity modeling utilizes either the Jossi-Stiel-Thodos or Pedersen correlations. Key assumptions include:

- Eccentricity of molecules
- Use of random mixing rules
- Binary interaction parameter
- Minimum Gibbs energy as an equilibrium criterion
- Fugacity as a function of measurable properties
- Volume translation used to improve density prediction.

Table 3 describes the processes used in the computational model for this application and includes:

- Convective and dispersive flow
- Relative permeability hysteresis
- Gas solubility in aqueous phase
- Aqueous
- Mineralization

All these processes were included in the computational model, and no additional mechanisms are anticipated. It is also possible to assess the confining layer integrity with geomechanical modeling. An initial assessment was conducted using data from the literature, which will be updated when data from the injection or monitoring wells has been acquired.

Table 3: Processes captured in the computational modeling

Computational Modeling Processes	Description
Convective Flow	Movement of CO_2 through the pore space during the injection period
Dispersive Flow	Result of gravity segregation and increasing CO_2 solubility in water
Relative Permeability Hysteresis	Trapping of CO_2 in pore spaces because of imbibition (increase in wetting phase saturation), which occurs during gravity segregation
CO_2 Solubility	Modeled by a modified form of Henry's law
Aqueous Ions	Small amount of CO_2 is ionized in H_2O
Mineralization	Long-term trapping mechanism that occurs over thousands of years

As the computational model uses the static model as input, it covers the same area as the static model but is focused on the storage intervals (Figure 3 and Figure 4).

1.2. Site Geology and Hydrology

All information regarding the site geology and hydrology are provided in the Project Narrative (Attachment 1:Project Narrative 2023). This includes the associated figures such as geologic maps, hydrologic maps, cross sections, and local stratigraphic columns.

1.3. Model Domain

The static and computational model domain information is summarized in Table 4. [redacted] Sensitive, Confidential, or Privileged [redacted]

~~**Table 4: Static model and computational model domain information. fbsl=feet below sea level**~~

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1.4. Porosity and Permeability

1.4.1. Petrophysical Modeling

The Project Narrative includes a discussion of the wells in the region that provided important porosity and permeability data for the Vervain Project, as well as the petrophysical analysis that was completed on these wells (Attachment 1:Project Narrative 2023).

The Vervain Project static model statistically represents available subsurface data and honors the conceptual understanding of regional and local geology. Cell height plays a significant role in upscaling porosity and permeability logs and must balance the goals of capturing vertical heterogeneity and maintaining a manageable cell-count and computing time (Table 5). The proportional vertical layering used for the Vervain Project static model captures variability observed in core data from multiple wells and honors thin intervals in the injection zone that may represent significant permeability streaks. The permeability was calculated from the transforms presented in the Project Narrative (Attachment 1:Project Narrative 2023).

The interpolated petrophysics from the static model were sampled and redistributed using a Gaussian random function simulation (GRFS) and variogram parameters obtained from (Illinois Basin - Decatur Project Dataset 2022) (Table 6). The vertical variogram range was defined from well log variogram analyses. Figure 6 and Figure 7 show the upscaled effective porosity and permeability values for the storage and confining zones at the two injectors NV_INJ1 and NV_INJ2, respectively. Figure 8 is a flow capacity (KH) map for the primary and secondary storage zones. Figure 9 and Figure 10 display the effective porosity and permeability distribution on cross section B-B' through the project site. These figures show that the Mt. Simon Arkose/Lower Mt. Simon Sandstone injection zone has the highest distributed porosity and permeability values. The Eau Claire Formation confining zone has the lowest porosity and permeability values, and the Middle/Upper Mt. Simon Sandstone and Eau Claire Silt storage zone has slightly lower porosity and permeability values relative to the underlying injection zone. Sensitive, Confidential, or Privileged Information [redacted] Figure 11 and Figure 12 display the effective porosity and permeability histograms for the model, respectively, that were distributed throughout static model, and these histograms reflect the porosity and permeability trends described above.

During the generation of the static model, statistical analyses were used to identify and correct any potential errors with the data distribution. Presently, the Vervain Project static model statistically represents the subsurface with the available input data. However, uncertainty will be significantly reduced once site specific data is acquired through the Pre-Operational Testing Program (Attachment 5: Pre-Op Testing Program 2023). Geophysical logs, core, well test data, and three-dimensional (3D) surface seismic surveys will be collected during the pre-operational phase of the project. Wireline logs from NV_INJ1, NV_INJ2, and NV_OBS1 will be used to calibrate 3D surface seismic data and produce inversion products such as porosity and lithology cubes for the area of the surface seismic survey. The logs can also be used to generate a discrete facies log, which can be combined with the lithology cube to provide insight regarding the local depositional setting. The static model will be updated with this newly acquired data and used in the computational modeling discussed in Section 4.5.

The conclusions of the geologic, petrophysical, and statistical analyses include:

- The successful CO_2 injection project at the Illinois Basin–Decatur Project (IBDP) (35 miles to the southeast) has proven that the storage system to be used at the Vervain Project Site can support a large-scale CO_2 injection project (Illinois Basin - Decatur Project Dataset 2022).
- The Eau Claire Formation is a thick, low permeability confining zone.
- The Lower Mt. Simon Sandstone/Mt. Simon Arkose thickness and petrophysical properties indicate that it will have adequate injectivity and storage capacity to accommodate the proposed injection volumes over the operation life of the project.
- The Middle Mt. Simon/Upper Mt. Simon/Eau Claire Silt will serve as secondary storage for the project.
- The static model will be updated with site specific data as project wells are drilled and more data becomes available.

Table 5: Summary of static model zones, dimensions, average effective porosity (%), average permeability in millidarcies (mD), geologic prognoses for the two injection wells (NV_INJ1 and NV_INJ2) including measured depth (MD) in feet, elevation in feet below sea level (fbsl), and thickness in feet, and KH values for the confining and storage zones in MD-feet.

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Figure 6: CBI: NV_INJ1 static model petrophysical prognosis with a focus on the storage and confining formations. Tracks include measured depth (MD), subsea vertical depth (TVDSS), upscaled effective porosity (PHIE Regional), upscaled permeability (mD), age, group, formation, and zone of use.

Figure 7: CBI: NV_INJ2 static model petrophysical prognosis with a focus on the storage and confining formations. Tracks include measured depth (MD), subsea vertical depth (TVDSS), upscaled effective porosity (PHIE Regional), upscaled permeability (mD), age, group, formation, and zone of use.

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Figure 8: Static model permeability*thickness (KH) map of the primary and secondary storage zones, which shows KH at the injectors to be between 33,000-34,000 MD-feet. NV_INJ1 and NV_INJ2 are injection wells and cross section B-B' is shown in Figure 9 and Figure 10.

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Figure 9: Cross section B-B' formations static model effective porosity property distribution showing the vertical and lateral heterogeneity. The location of cross section B-B' is shown in Figure 8.

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Figure 10: Cross section B-B' formations and static model permeability property distribution showing the vertical and lateral heterogeneity. The location of cross section B-B' is shown in Figure 8.

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Figure 11: Static model effective porosity histograms for the storage system filtered by formation and subdivisions within the model. A) Eau Claire Formation confining zone, B) the Eau Claire Silt and Upper Mt. Simon Sandstone storage zone, C) the Middle Mt. Simon Sandstone storage zone, D) the Lower Mt. Simon Sandstone injection zone, E) the Mt. Simon Sandstone Arkose injection zone, and F) the Argenta Formation lower confining zone.

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Figure 12: Static model permeability (mD) histograms filtered by formation and subdivisions within the model. A) Eau Claire Formation confining zone, B) the Eau Claire Silt and Upper Mt. Simon Sandstone storage zone, C) the Middle Mt. Simon Sandstone storage, D) the Lower Mt. Simon Sandstone injection zone, E) the Mt. Simon Sandstone Arkose injection zone, and F) the Argenta Formation lower confining zone.

1.5. Constitutive Relationships and Other Rock Properties

A generalized gas-liquid relative permeability curve was used in the model (Figure 13). Laboratory curves are not currently available, but the curves used are consistent with published curves in the literature and include gas relative permeability hysteresis that is an important gas trapping mechanism. Calculation of the imbibition gas relative permeability curve is described below, from the GEM user's manual:

> "For a non-wetting phase (gas) consider a typical drainage process (increasing gas saturation) reaching a maximum gas saturation, S_{gh}, followed by an imbibition process (decreasing gas saturation) leading to a trapped gas saturation, S_{grh}."

The gas relative permeability on the drainage to imbibition scanning curve for a given value of the gas saturation, S_g, is given by:

$$k_{rg}(S_g) = k_{rg}^{drn}(S_{gf}) \qquad (1)$$

where the free gas saturation S_{gf} is calculated from the following relationship:

$$S_{gf} = S_{gcrit} + \frac{(S_g - S_{grh})(S_{gh} - S_{gcrit})}{(S_{gh} - S_{grh})} \qquad (2)$$

(S_{gh} is the maximum gas saturation, S_{gcrit} is the critical gas saturation)

Capillary pressure laboratory data is not currently available but is thought to be relatively insignificant for a gas-water system in a highly permeable zone. During the Pre-operational Testing Program, core will be acquired from the injection interval that will allow the capillary pressure for the site to be established.

The rock compressibility values used in the model were derived from nearby carbon capture and sequestration (CCS) projects. Site specific rock compressibility values will be obtained when the wells are drilled for the project as per the Pre-operational Testing Program (Attachment 5: Pre-Op Testing Program 2023).

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Figure 13: Gas-liquid relative permeability curves used in the Vervain Project model, including hysteresis.

1.6. Boundary Conditions

In the computational model, an aquifer function (Carter-Tracy) was applied to the grid boundary (side). The top and bottom of the grid are considered no-flow boundaries. The formation was allowed to "leak", i.e., accept fluids from the grid. This approach was used to simulate the pressure response of an infinite-acting aquifer and is considered preferable to using large pore volumes on edge grid blocks.

1.6.1. Initial Conditions

Initial conditions for the computational model reported in Table 7. These initial conditions include datum, pressure, temperature, and salinity.

Table 7: Initial conditions and data sources for the computational model. °F=degrees Fahrenheit, psia=pounds per square inch absolute, psi/ft=pounds per square inch/foot, ppm=parts per million dissolved solids.

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1.6.2. Operational Information

Details of the proposed Vervain Project injection operations are presented in Table 8 including coordinates, depths, wellbore diameter in inches, and planned injection periods.

Table 8: Injection operational details for the Vervain Project including coordinates, perforated intervals, wellbore diameter, and injection details.

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1.6.3. Fracture Pressure and Fracture Gradient

Calculated fracture gradient and maximum injection pressure values are given in Table 9. Fracture gradient was estimated from mini-fracs and step-rate tests performed for the IBDP (Greenberg, 2021). The IBDP data is considered a suitable analog for the Vervain Project given its proximity to the IBDP site. The project plans to perform step-rate tests in the Mt. Simon Sandstone to determine the fracture gradient at the project site as part of the Pre-Operational Testing Program (Attachment 5: Pre-Op Testing Program 2023). The project specific fracture gradient will be updated in the computational model once it is available.

Table 9: Injection pressure details at the NV_INJ1 and NV_INJ2 injection wells, including fracture gradient, maximum pressure gradient, ground elevation, and perforation information.

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2. Computational Modeling Results

2.1. Predictions of System Behavior

The following figures have been created to display the predicted behavior of the CO_2 plume during injection and post injection monitoring periods.

- Figure 14 is a cumulative graph of the CO_2 injection (1.25 million tonnes per annum (Mtpa) for each injector well; 2.5 Mtpa total).
- Figure 15 is a cross section view of the CO_2 plume in year 75 (50-years post injection).
- Figure 16 shows the predicted CO_2 plume development during injection and during the post injection period.
- Figure 17 shows the maximum extent of the pressure front at the end of the operational phase (Year 25/end of injection), as well as an outline of the CO_2 plume at 50 years post-injection (Year 75).
- Figure 18 and Figure 19 display the CO_2 plume development over time along cross section B-B'.
- Figure 20 is a 3D view of the CO_2 plume overlying the Argenta Formation.
- Figure 21 and Figure 22 are the predicted fall-off in bottom hole pressure and tubing pressure at NV_INJ1 and NV_INJ2, respectively, after 50 years post-injection.

The CO_2 plume radius after 25-years of injection is predicted to have an area of approximately 8 mi^2 (Figure 16). After 10 years post-injection, the CO_2 plume enlarges slightly to 8.3 mi^2 due to the segregation of fluids by gravity, and modeling shows CO_2 plume stabilization and insignificant plume expansion (Figure 16).

Sensitive, Confidential, or Privileged Information If subsequent testing and monitoring data acquired over the operational phase of the project suggests a different delta pressure value is appropriate, the AoR will be re-evaluated.
Key uncertainties for the project currently include:

- Storativity (porosity x height)
- Injectivity or flow capacity (permeability x height)
- kv/kh ratio (vertical permeability divided by horizontal permeability)

When the first well is drilled for the project, the data gathered as part of the Pre-operational Testing Program will be used to refine these parameters, and the project models will be updated (Attachment 5: Pre-Op Testing Program 2023). Significant changes in the AoR are not expected, and the pressure front is expected to shrink rapidly post injection.

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Figure 14: CO_2 injection schedule highlighting injection, post-injection monitoring, and site closure intervals in years.

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Figure 15: Cross section B-B' (Figure 8) with the predicted Year 75 (50-year post injection) CO_2 plume represented as gas saturation. MNSM=Mt. Simon Sandstone, vertical exaggeration=5x, and ft=feet.

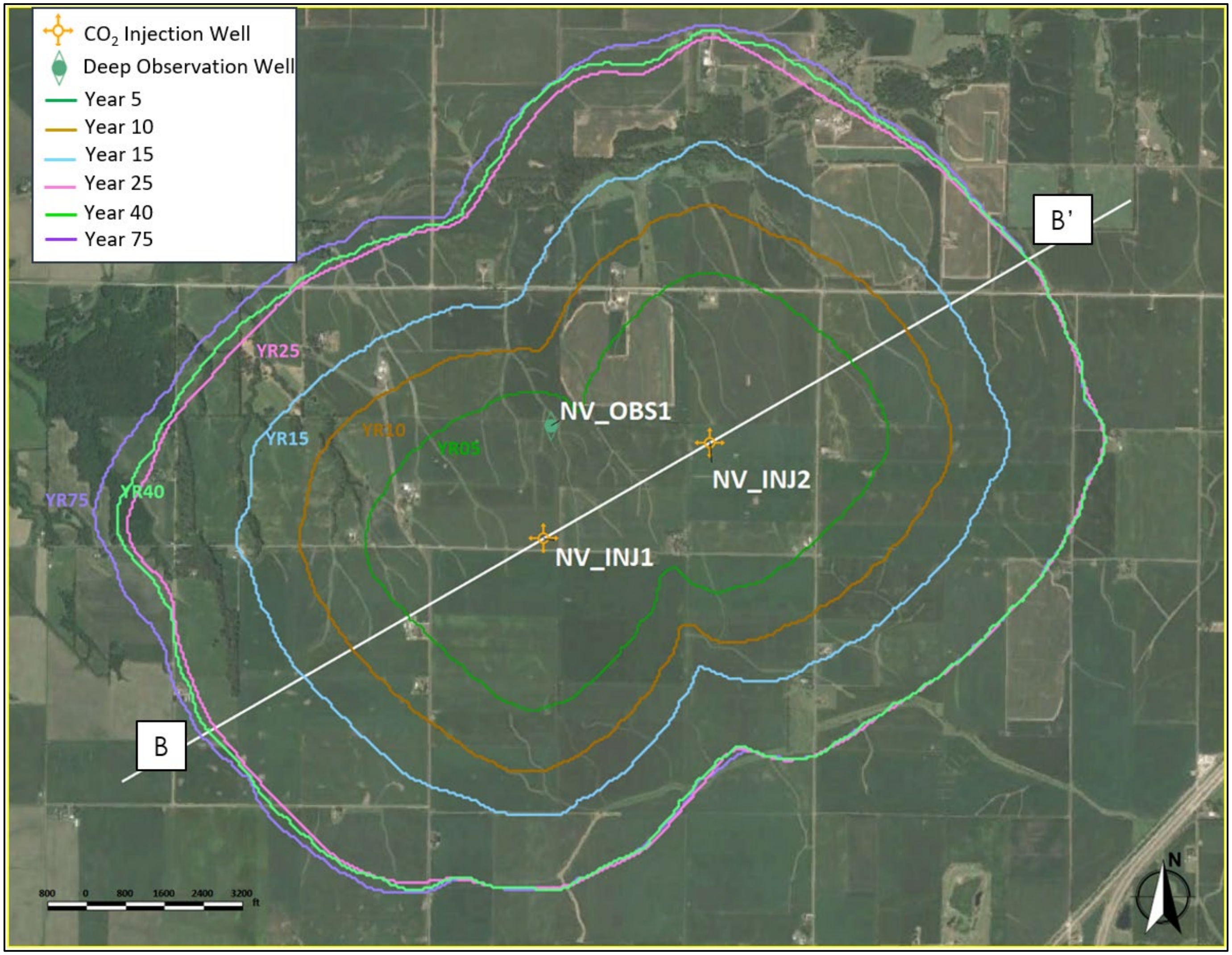

Figure 16: CO_2 plume development map over years 5, 10, 15, 25 of the injection operations as well as years 40 (15 years post injection) and 75 (50 years post injection). The map indicates by year 40 the CO_2 plume has stabilized. NV_INJ1 and NV_INJ2 are the injection wells, and NV_OBS1 is the observation well. Cross section B-B' is shown in Figure 18 and Figure 19.

Figure 17: Predicted maximum extent of the project AoR, as predicted by the 137-psi delta pressure at the end of the operational phase of the project in Year 25 (end of injection). The outline of the CO_2 plume at 50 years post-injection (Year 75) is also shown. NV_INJ1 and NV_INJ2 are the injection wells, and NV_OBS1 is the observation well.

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Figure 18: CO_2 plume development in the Mt. Simon Arkose (Arkose_Prog) and the Lower Mt. Simon Sandstone (MNSM_Lower_Prog) along cross-section B-B' (Figure 8) at years A) 5, B) 10, and C) 15 of injection operations. The plume is represented by gas saturation, vertical exaggeration=5x, the horizontal scale=3,000 feet, and MNSM=Mt. Simon. NV_INJ1 and NV_INJ2 are injection wells, and NV_OBS1 is the observation well.

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Figure 19: CO_2 plume development in the Mt. Simon Arkose (Arkose_Prog) and the Lower Mt. Simon Sandstone (MNSM_Lower_Prog) along cross-section B-B' (Figure 8) at years A) 25 end of injection operations, B) 40, and C) 75 post-injection period. The plume is represented by gas saturation, vertical exaggeration=5x, the horizontal scale=3,000 feet, and MNSM=Mt. Simon. NV_INJ1 and NV_INJ2 are injection wells, and NV_OBS1 is the observation well

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Figure 20: Three-dimensional perspective of the CO_2 plume along B-B' (Figure 8) at year 75 (50 years post injection) overlying the Argenta Formation surface.

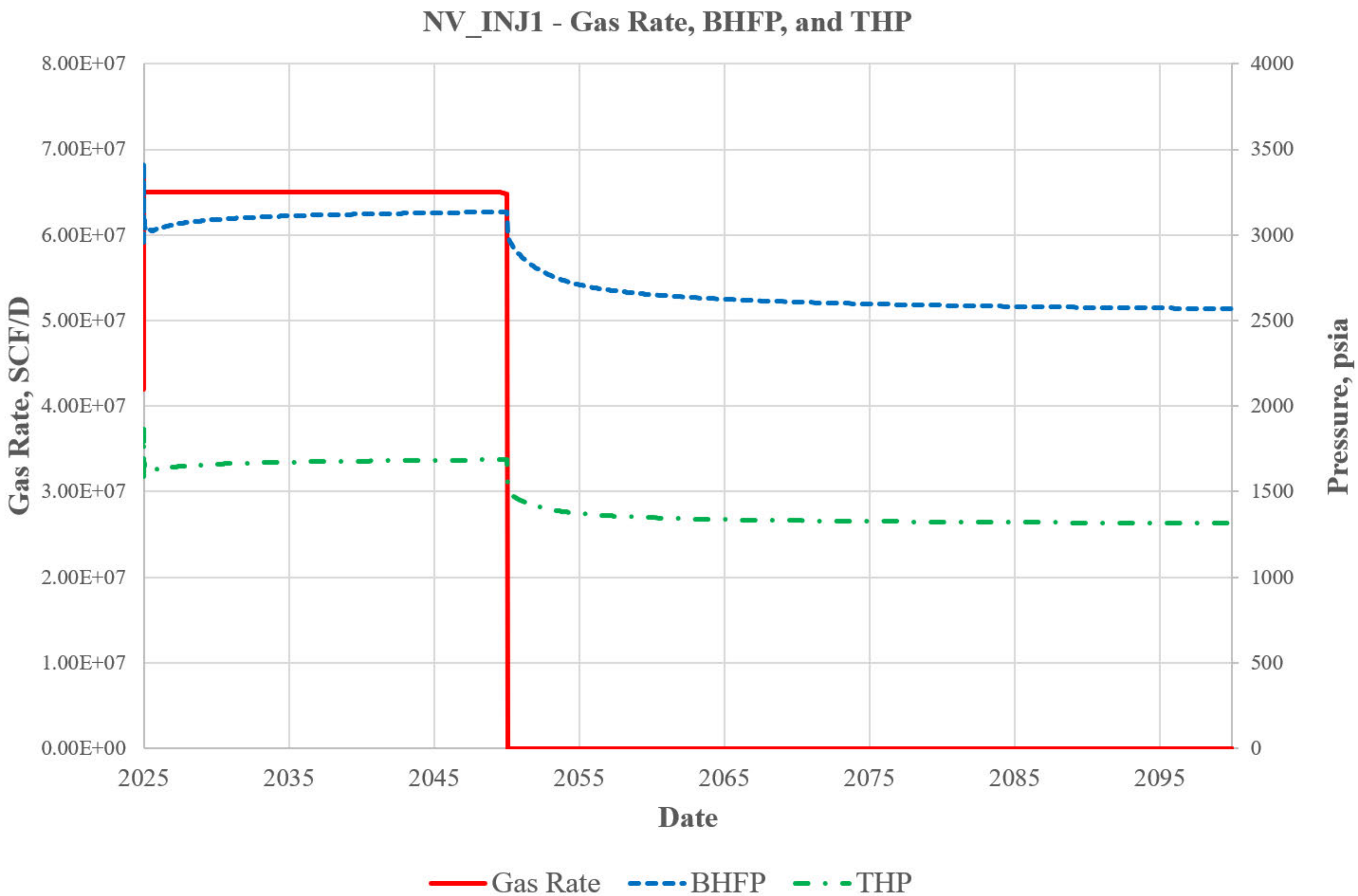

Figure 21: Predicted fall-off in bottomhole (BHFP) and tubing head (THP) pressures once injection operations cease after 50 years post-injection for NV-INJ1.

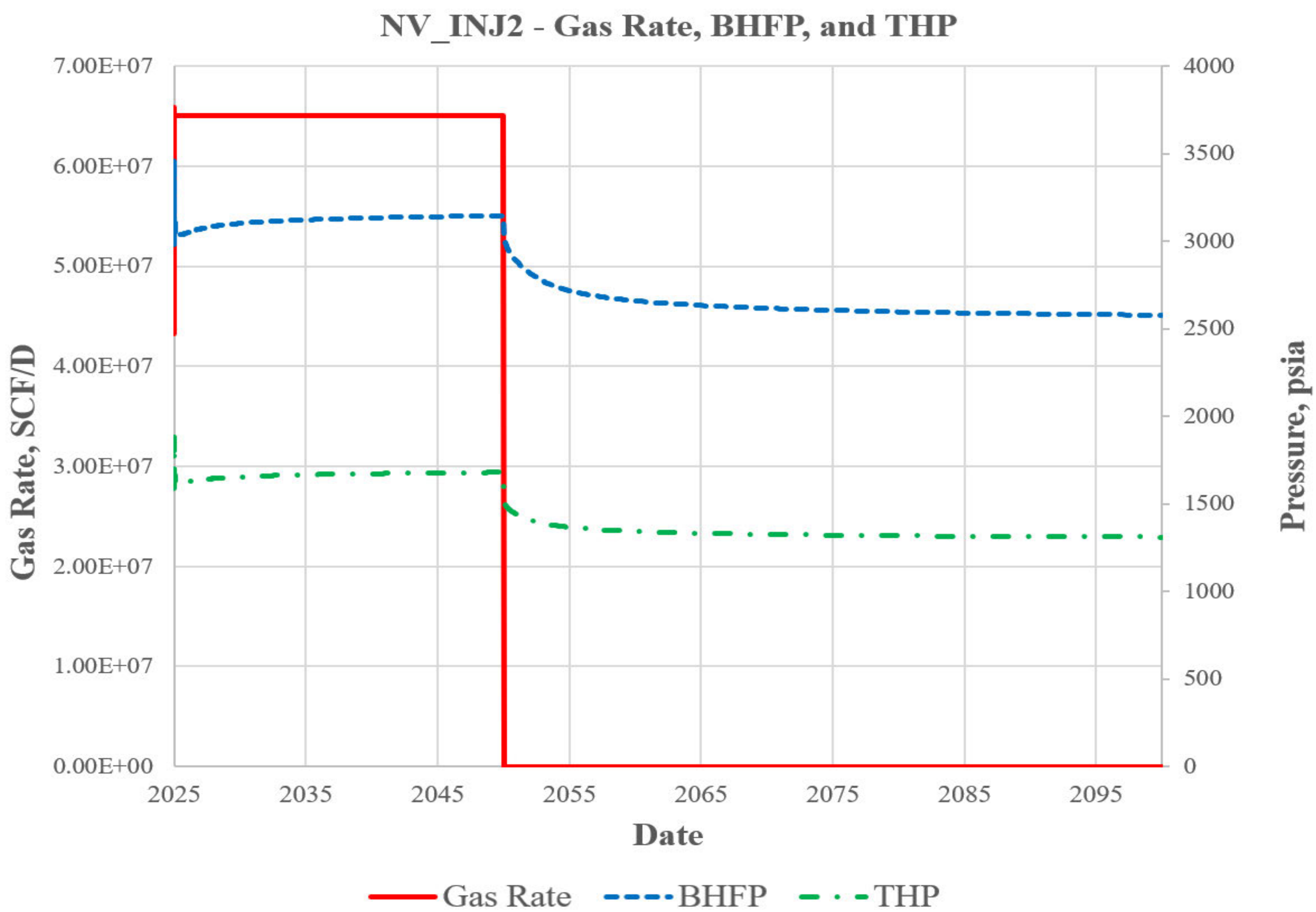

Figure 22: Predicted fall-off in bottomhole (BHFP) and tubing head (THP) pressures once injection operations cease after 50 years post-injection for NV_INJ2.

Table 10 and Figure 23 show the proportion of the mass of the injected CO_2 trapped by the five mechanisms at 100 years post-injection. Structural and residual gas trapping are the dominant trapping mechanisms 100 years post-injection at the Vervain Project Site.

Table 10: CO_2 trapping mechanisms and percentages trapped 100 years post-injection.

Trapping Mechanism	% CO_2 trapped 100 years post-injection
Structural	44.51
Residual (immobile) gas	39.98
Dissolved gas	12.05
Aqueous ions	3.16
Mineralization	0.31

Initially, a large percentage of the CO_2 is structurally trapped. As the fluids gravity segregate, the amount of residual (immobile) gas increases. Dissolution of CO_2 into brine also begins but at a slow rate. Dissociation of dissolved CO_2 into aqueous ions also occurs but accounts for a small percentage of the trapping. Mineralization is a slow process that generally takes hundreds or thousands of years to become a significant trapping mechanism and is not expected to play a significant role in trapping CO_2 for hundreds of years.

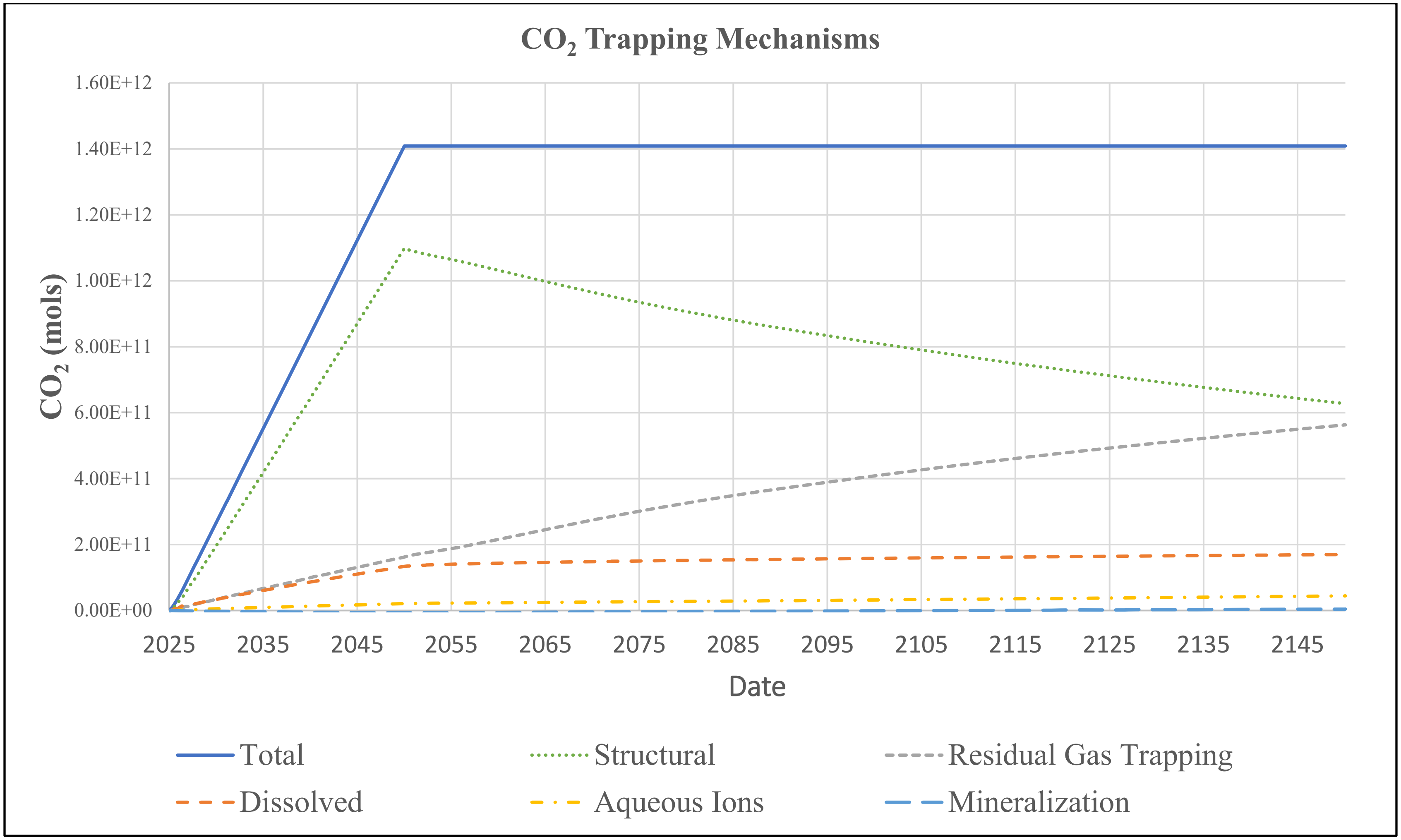

Figure 23: Graph of the relationship and evolution of CO_2 trapping mechanisms over time at the Vervain Project.

2.2. Model Calibration and Validation

History matching was not performed as there is no current injection data available. The model was constructed using all available reference information from the IBDP, CarbonSAFE Illinois – Macon County, and Future Gen CCS projects. Included in the reference information are well test results that allow calibration of the computational model for various parameters including permeability in both the horizontal and vertical directions.

Frailey (2021) presented an analysis of well testing at T.R. McMillen#2 conducted as part of CarbonSAFE Illinois – Macon County including a summary of interpreted well test results of kv/kh for the Mt. Simon Sandstone interval. The values ranged from 0.000016 to 0.03 and the average kv/kh was 0.009 when considering the ranges for each test. Based on this data a base case kv/kh of 0.01 has been used and a range constructed with kv/kh values of 0.001, 0.01, and 0.1. The models were run for a 25-year injection period followed by a 50-year post-injection period. The results show that the CO_2 plume will increase in size as kv/kh increases. The plume area for each case is 7.9, 8.6, and 11.9 square miles (mi^2), respectively. Table 11 and Figure 24 demonstrate the effect of kv/kh on the relative size of the CO_2 plume.

Table 11: Impact of varying kv/kh values on the CO_2 plume radius.

kv/kh	CO_2 Plume Area (mi^2)
0.001	7.9
0.01 (Base case)	8.6
0.1	11.9

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Figure 24: Relative CO_2 plume size 50-years post-injection for kv/kh of 0.001, 0.01, and 0.1.

3. AoR Delineation

3.1. Critical Pressure Calculations

To delineate the pressure front radius, a minimum (or critical) delta pressure was calculated. The delta pressure is the increase in pressure necessary to overcome the hydrostatic head of the injection zone fluid and would allow fluids to migrate up an open conduit to the lowermost USDW in the unlikely event that such a conduit exists. The formula for calculating the delta pressure is given below (source: UIC Program Class VI Well Area of Review and Corrective Action Evaluation Guidance)

$$\Delta P_{if} = P_u + \rho_i * (z_u - z_i) - P \quad (3)$$

Where:
ΔPif = delta pressure,
Pu = initial pressure of the lowermost USDW,
ρi = fluid density of the injection zone,
g = acceleration due to gravity,
zu = elevation of the lowermost USDW,
zi = elevation of the injection zone, and
P = initial pressure of the injection zone. Substituting appropriate values into the equation, a minimum delta pressure was calculated to be 137 psi.

3.2. AoR Delineation

The Vervain Project AoR was initially selected by observing the delta pressure of each grid block in the model after 25 years of injection. The grid blocks that had a delta pressure equal to or greater than the minimum delta pressure (calculated above) and considered to be in the AoR.

Through the Pre-operational Testing Program, uncertainties around the injection zone parameters will be addressed, and the static and computational models will be updated with the new data (Attachment 5: Pre-Op Testing Program 2023).

The new computational model will be used to re-evaluate the CO_2 plume and pressure front, and the AoR will be revised if necessary. NV_OBS1 will be used to monitor changes in injection zone pressure and aqueous geochemistry at a distance from the injection wells (Attachment 7: Testing And Monitoring Plan 2023). The computational model will be updated to match the observed data over the life of the project. If the injection zone does not perform as predicted, the AoR will be re-assessed if necessary.

4. Corrective Action

EPA Class VI regulations require the identification of all confining zone penetrations within the AoR because these wells could become a preferential pathway for leakage of CO_2 and/or formation brine fluids out of the injection zone. If necessary, corrective actions will need to be performed on the penetrations to prevent leakage that could potentially cause endangerment to a USDW. The following sections discuss the findings of an evaluation that was performed to:

- Identify existing penetrations within the vicinity of the AoR,
- Determine if any penetrations extend below the primary confining zone, thereby presenting a risk of leakage that may require corrective actions,
- Identify corrective actions and define the approach that will be taken to prevent leakage that could endanger a USDW.

4.1. Tabulation of Wells Within the AOR

4.1.1. Oil and Gas Wells

Sensitive, Confidential, or Privileged Information [redacted] These well data were collected from several sources that include Illinois Water and Related Wells website (IL Water; Prairie Research Institute) and the Illinois State Geologic Survey website. Of the 26 O&G wells within the AoR, twelve are reported to be less than 300 feet deep, seven are categorized as stratigraphic or structure test wells, eleven are abandoned, and eight produce gas from glacial sediments (Illinois Oil and Gas Resources 2022). These shallow wells are not considered to be a risk for this project.

Sensitive, Confidential, or Privileged Information [redacted] (Figure 26). Figure 27 to Figure 30 display wells that penetrate progressively deeper formations. Within the AoR, eleven wells penetrate the New Albany Formation (Figure 27), and five O&G wells penetrate the Maquoketa Formation (Figure 28). IL121130001000 and IL121070001601 are the deepest wells within the AoR and penetrate the Trenton Formation to depths of 2,115 and 2,165 feet, respectively (Figure 29). These two wells are located approximately 7.2 miles and 6.9 miles, respectively, from the nearest CO_2 injector and are both dry and abandoned O&G wells drilled in 1941. The tabulated well data has been uploaded as a separate file. No wells penetrate the St. Peter Formation (lowermost USDW) within the AoR (Figure 30).

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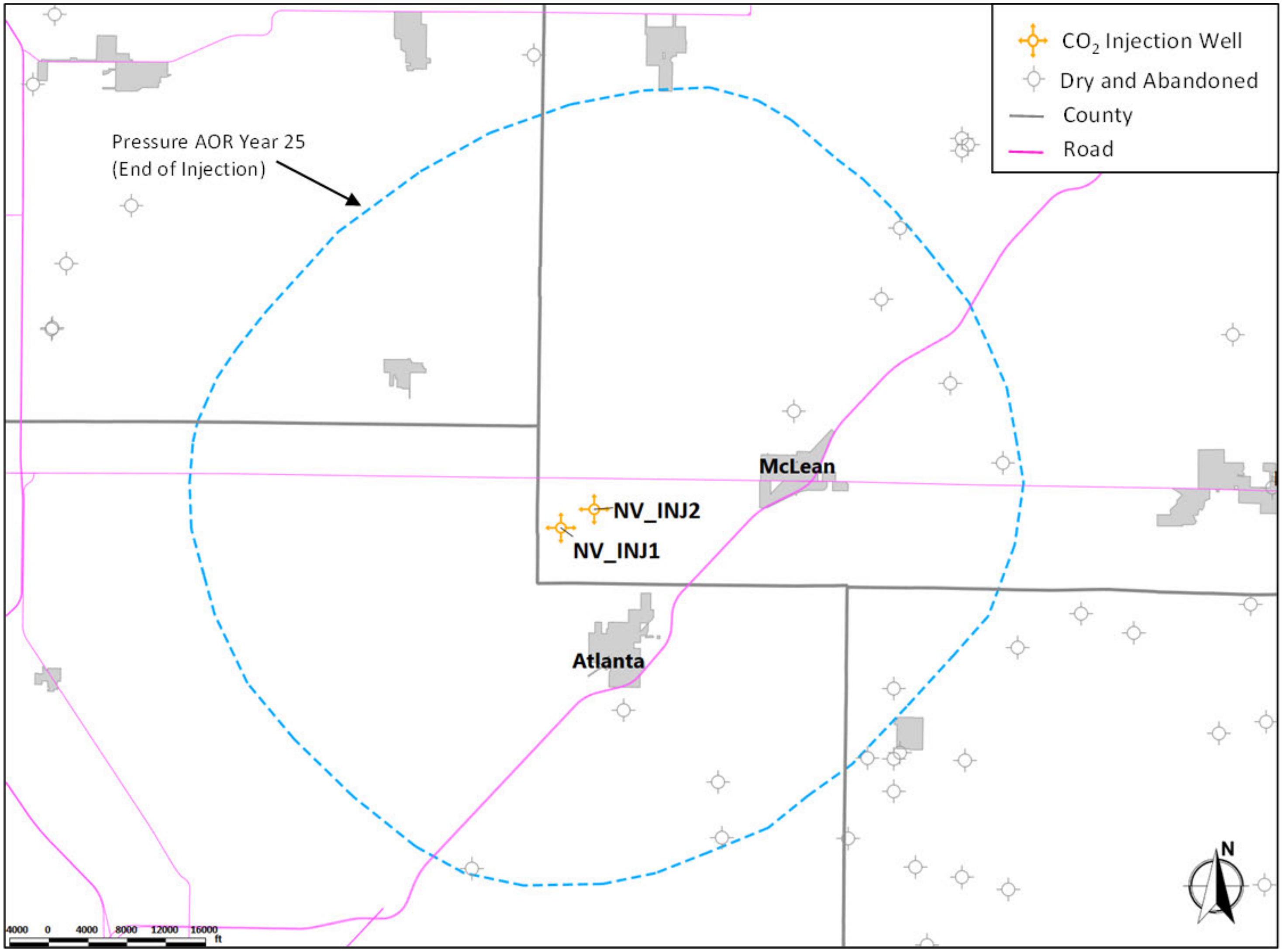

Figure 27: Eleven O&G wells penetrate the New Albany Formation within the AoR.

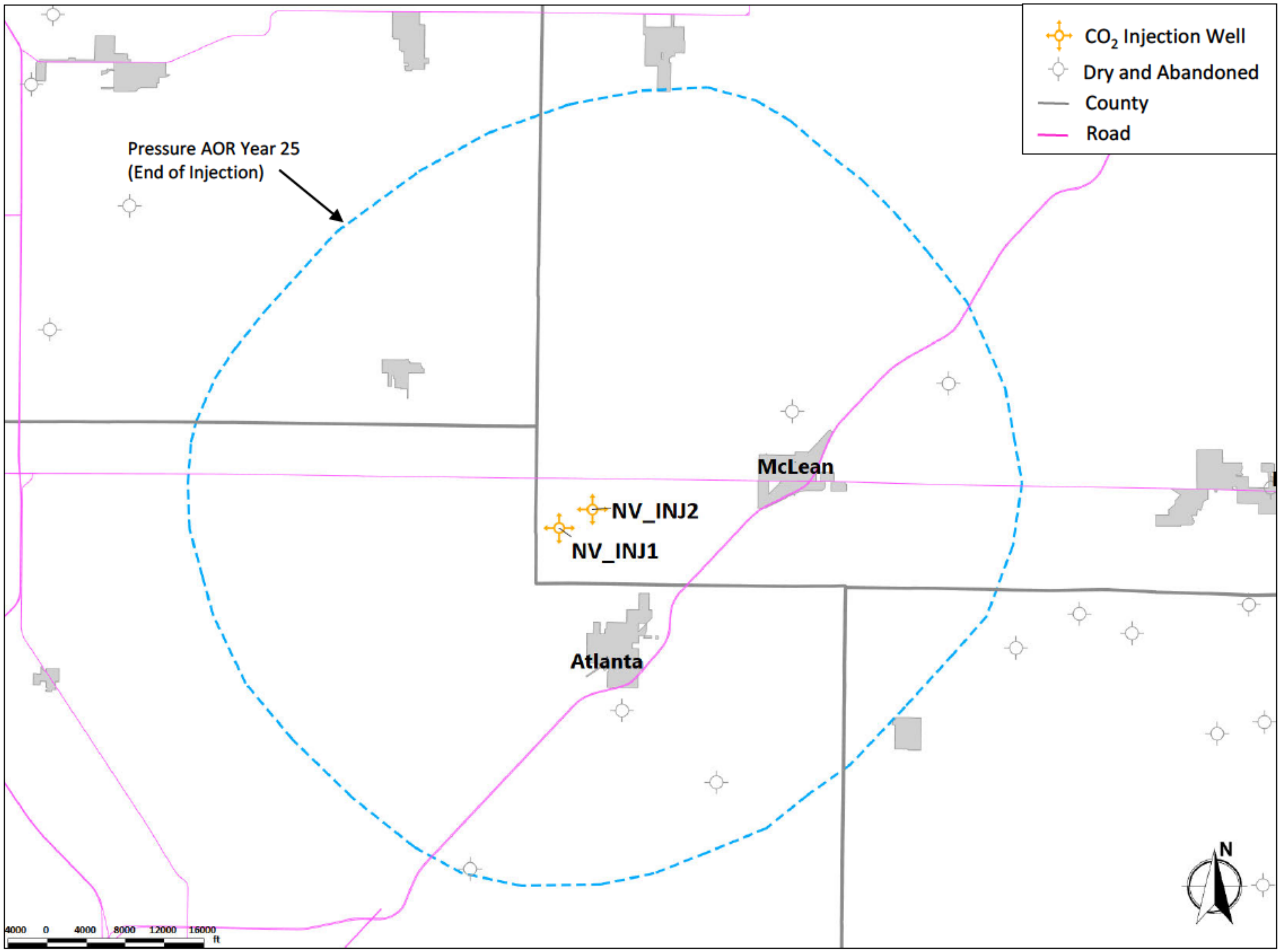

Figure 28: Five O&G wells penetrate the Maquoketa Formation within the AoR.

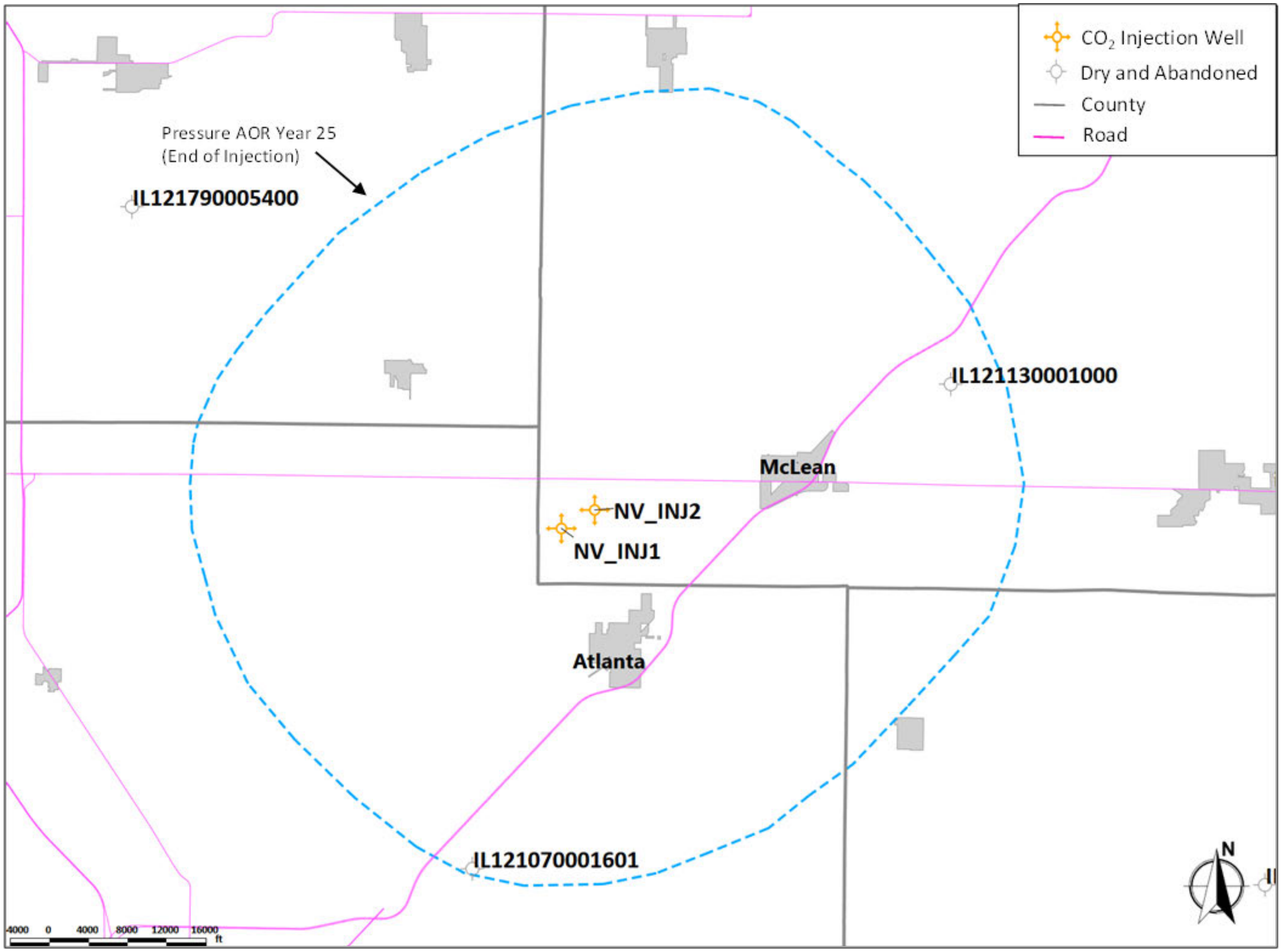

Figure 29: Two O&G wells penetrate the Trenton Formation within the AoR.

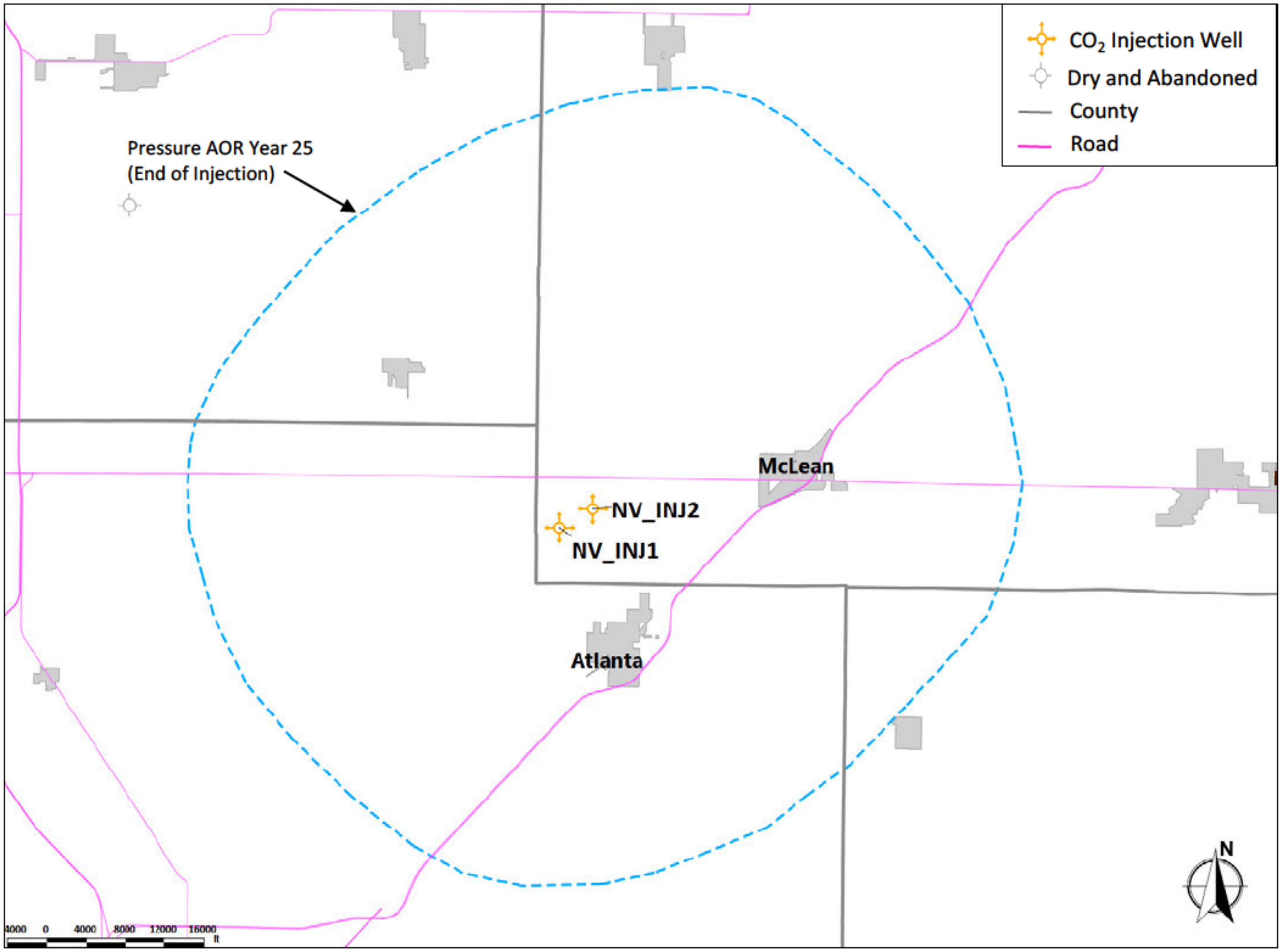

Figure 30: There are no wells that penetrate the St. Peter Formation within the AoR.

4.1.2. Water Wells

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4.2. Wells Within the AoR
Details of the O&G and water wells have been provided in the preceding section. The IHS Energy, Illinois Water, and Illinois Oil and Gas Resources websites were used to compile the data for this section. No deep wells penetrate the Eau Claire Formation confining zone in the project AoR. It is believed that all historical wells in the AoR have been captured by the above data sources.

4.2.1. Wells Penetrating the Confining Zone
As no wells penetrate the Eau Claire Formation confining zone, corrective action is not required for the Vervain Project. The deepest wells in the Trenton Formation are IL12113000100 (extends to 2,115 feet below ground level) and IL121070001601 (extends to 2,165 feet below ground level, Figure 29), both of which are located approximately 7 miles from the nearest CO_2 injector.

4.3. Plan for Site Access
Surface use and pore space lease agreements have been negotiated with area landowners to access the land that the project wells are located on for the life of the project. Surface use agreements will be put in place to allow surface access for periodic 3D seismic data acquisition as well as periodic water sampling. As per the surface use agreements, proper notification will be given prior to accessing a property to collect water samples.

4.4. Corrective Action Schedule
Currently no wells within the AoR require corrective action. As such, no corrective action schedule is currently necessary.

4.5. Re-evaluation Schedule and Criteria

4.5.1. AoR Re-evaluation Cycle
The Vervain Project AoR will be updated when site specific data from the project wells and seismic surveys are available, and it will be re-evaluated every five years during the injection and post-injection phases of the project. Additionally, any significant changes to the CO_2 stream or an increase in the injection volumes will trigger a re-evaluation of the AoR.

As part of this re-evaluation, monitoring and operational data will be used to monitor the performance of the injection wells and injection zone as well as calibrate the computational modeling. The testing and monitoring data will include (but is not limited to) the following:
- Surface and bottomhole pressure (BHP)
- Total mass injected and mass injection rates
- Mechanical integrity logs
    - Temperature logs
    - Pulsed neutron logging (PNL)
- Time-lapse 3D seismic data
- Passive seismic monitoring

In addition to reviewing the testing and monitoring data on five-year intervals, this data will also be assessed on an annual basis to monitor for any unexpected changes in behavior. Should notable deviations from the computational modeling results occur, the modeling will be re-run, and a new AoR will be re-established. Notable deviations are defined in the following section.

4.5.2. Triggers for AoR Re-evaluations Prior to the Next Scheduled Re-evaluation

Table 12 presents a non-exhaustive list of potential parameters that would trigger a re-evaluation of the AoR prior to the next scheduled re-evaluation should notable deviations from anticipated values occur.

Table 12: List of potential parameters that could initiate re-evaluation of the AoR. (Note that this list is non-exhaustive.)

Monitoring Parameter	Description
Pressure	• Sustained variations in pressure outside of three standard deviations from the average
Temperature	• Variations in temperature observed during MIT logging activities that are determined to be a mechanical integrity issue • Sustained variations in temperature outside of three standard deviations
CO_2 Saturation	• Increased CO_2 saturations that indicate migration of CO_2 above the confining zone and are not a result of a mechanical integrity issues
Groundwater Constituent Concentrations	• Changes in fluid and chemical content concentrations that indicate migration of injection zone fluids into formations overlying the confining zone, which are not a result of a mechanical integrity issue • Should a statistically significant deviation from the baseline data collected from the above confining zone interval occur
Bottomhole Injection Pressure	• Should bottomhole pressure exceed 90 percent of the calculated fracture pressure
Well Integrity	• Change in pressure in the annulus system surrounding the injection well that indicates a loss of mechanical integrity in an injection well will be investigated
Passive Seismic Monitoring and Induced Seismicity	• Seismicity monitoring indicates the re-activation of faults or fractures that could propagate into the confining layer and impact containment

Additional causes for AoR re-evaluation could include the extension of the CO_2 plume or pressure front beyond the initial plume predictions based on results of 3D seismic surveys; induced seismic events greater than M3.5 within the seismic monitoring area around the project; an exceedance of any operating conditions; or, if the data gathered during the Pre-Operational Testing Program result substantially changes to the current models and understanding of the subsurface.

Should any of the events occur that are detailed above, the project team will discuss AoR re-evaluation procedures and timeline with the UIC Program Director to conclude if the re-evaluation is necessary.

5. References

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2023. *Attachment 5: Pre-Op Testing Program.* Class VI Permit Application Pre-Operational Formation Testing Program; Vervain.

2023. *Attachment 6A: NV_INJ1 Well Operations Plan.* Class VI Permit Application Injection Well #1 Operations Plan; Vervain.

2023. *Attachment 6B: NV_INJ2 Well Operations Plan.* Class VI Permit Application Injection Well #2 Operations Plan; Vervain.

2023. *Attachment 7: Testing And Monitoring Plan.* Class VI Permit Application Testing And Monitoring Plan; Vervain.

2023. *Attachment 8A: NV_INJ1 Well Plugging Plan.* Class VI Permit Application Injection Well #1 Plugging Plan; Vervain.

2023. *Attachment 8B: NV_INJ2 Well Plugging Plan.* Class VI Permit Application Injection Well #2 Plugging Plan; Vervain.

2023. *Attachment 9: PISC and SC.* Class VI Permit Application Post-Injection Site Care And Site Closure Plan; Vervain.

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