Class VI Injection Well Application

Attachment 07: Testing And Monitoring Plan
40 CFR 146.90

Linden Project

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Prepared by:

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Project Information

Project Name: Linden

Project Operator: Vault Alliance CCS, LP

Project Contact: Sensitive, Confidential, or Privileged Information [redacted]

Linden Sassafras Hill Injection Well 1 (LSH INJ1) Location:

Latitude: 40.210756°
Longitude: -86.865219°

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List of Acronyms

3D	three-dimensional
ACZ	above confining zone
ADM	Archer Daniels Midland
AoR	Area of Review
APT	annulus pressure test
ASTM	American Society of Testing and Materials
fbgl	feet below ground level
BHFP	bottomhole flowing pressure
CCS1	Illinois Basin–Decatur Project injection well at the ADM facility
CO_2	carbon dioxide
DIC	Dissolved Inorganic Carbon
DTS	Distributed Temperature Sensor
EPA	Environmental Protection Agency
EPSG	European Petroleum Survey Group
ERRP	Emergency and Remedial Response Plan
FOT	fall-off Test
GR	Gamma Ray
IBDP	Illinois Basin–Decatur Project
LA OBS1	Linden Antilles Deep Observation Well 1
LR ACZ1	Linden Ralter Above Confining Zone Monitoring Well 1
LSH INJ1	Linden Sassafras Hill Injection Well 1
MAIP	maximum allowable injection pressure
Mc	magnitude of completeness
MIT	mechanical integrity test
MS	mass spectrometry
PISC	Post Injection Site Care
PNL	Pulsed Neutron Logging
PSI	pounds per square inch
QA	Quality Assurance
QASP	Quality Assurance and Surveillance Plan
SCADA	supervisory control and data acquisition
SM	standard method
TBD	to be determined
TD	total depth
TDS	total dissolved solids
UIC	Underground Injection Control
USDW	Underground Source of Drinking Water

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1. Overall Strategy and Approach for Testing and Monitoring

The Testing and Monitoring Plan presented in this document provides details on how the Linden Project will monitor the site pursuant to 40 CFR 146.90.

1.1. Testing and Monitoring Plan Strategy

The Linden Project uses a risk-based Testing and Monitoring Program that includes operational, verification, and environmental assurance components that meet the regulatory requirements of 40 CFR 146.90. This Testing and Monitoring Program is based on experience gained from other approved Class VI projects, as well as extensive geologic evaluation and computational modeling.

Goals of the monitoring strategy include, but are not limited to:

- Fulfillment of the regulatory requirements of 40 CFR 146.90,
- Protection of underground sources of drinking water (USDW),
- Risk mitigation over the life of the project,
- Confirmation that Linden Sassafras Hill Injection Well #1 (LSH INJ1) is operating as planned while maintaining mechanical integrity,
- Acquisition of data to validate and calibrate the models used to predict the distribution of CO_2 within the injection zone, and
- Support Area of Review (AoR) re-evaluations over the course of the project.

The Testing and Monitoring Plan will be adaptive over time, and is subject to alteration should one of the following potential scenarios occur:

- Project risks evolve over the course of the project outside of those envisioned at the beginning of the project,
- Significant differences between the monitoring data and predicted computational modeling results are identified,
- Key monitoring techniques indicate anomalous results related to well integrity or the loss of containment.

Monitoring activities are considered within three categories based on objectives: operational, verification, and assurance monitoring.

- ***Operational monitoring*** focuses on day-to-day injection operations such as system performance.
- ***Verification monitoring*** confirms that the injected CO_2 remains contained within the selected storage complex. The CO_2 and pressure plume development are tracked over time to provide data for model calibration. Integration of verification monitoring data into project models allows the project to demonstrate conformance between the computational modeling and the testing and monitoring data collected during the operations and closure phases of the project's lifecycle.
- ***Assurance monitoring*** is performed at surface and near-surface (i.e., soil, groundwater, USDWs, etc.) to monitor for any changes from baseline (taken pre-injection) sample data that might indicate CO_2 migration towards surface.

The three monitoring categories encompass:

- Well operations,
- Containment,
- Non-endangerment of USDWs,
- Capacity,
- Injectivity,
- Injection pressure, and
- Conformance.

Table 1 provides of summary of the general monitoring strategy with subcategories.

Table 1: Summary of general monitoring strategy for the Linden Project

Monitoring Action	Monitoring Objectives	Monitoring Technology
CO_2 stream analysis	Purity of the CO_2 stream	Lab analysis
CO_2 plume monitoring	Verification/ conformance, containment, non-endangerment of USDWs	Time-lapse seismic data, pulsed neutron logging (PNL), fluid sampling with aqueous geochemistry, and isotope analysis
Pressure plume monitoring	Injection pressure, injectivity, verification/ conformance	Downhole pressure sensors in the injection wells, seismic monitoring
ACZ Changes	Containment, non-endangerment of USDWs	Downhole pressure sensors in monitor wells, fluid sampling with aqueous geochemistry and isotope analysis, PNL, time-lapse seismic data,
Project well integrity	Containment, non-endangerment of USDWs	Temperature logging, PNL, annular pressure monitoring, mechanical integrity tests (MIT), pressure fall-off tests (FOTs), corrosion monitoring, testing of emergency shut-down systems

Monitoring Action	Monitoring Objectives	Monitoring Technology
Reservoir performance	Injectivity	Wellhead and downhole pressure sensors
Induced seismicity	Containment, non-endangerment of USDWs, induced seismicity	Surface-based or downhole seismic monitoring arrays
Groundwater monitoring	Containment, non-endangerment of USDWs, assurance	Fluid sampling with aqueous geochemistry

1.2. Storage Complex

A site-specific stratigraphic chart of geologic formations present in LSH INJ1 is shown in Figure 1. A cross section of the CO_2 plume at the end of the ten-year post injection site care (PISC) period is shown in Figure 4. The specific intervals to be monitored are as follows:

- Mt. Simon Sandstone (injection interval),
- Ironton-Galesville Sandstones (Above Confining Zone (ACZ) interval),
- Borden Group in the Mississippian sediments (lowermost USDW),
- Shallow groundwater.

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Figure 1: Site-specific stratigraphic column with age, nomenclature, generalized lithology, and zone of use.

1.3. AoR and Project Wells

Figure 2 and Table 2 show and describe the proposed well locations for the project. Figure 2 shows the predicted plume extent 50 years post injection and the pressure defined AoR at end of the injection period. Figure 3 and Figure 4 illustrate the modeled CO_2 plume development 10 to 50-years post injection relative to the AoR. The CO_2 and pressure plume simulation predictions have been used to inform the spatial extent of the Testing and Monitoring Plan.

The AoR and Corrective Action Plan includes a discussion of the technical basis for determination of the current AoR as well as how the monitoring data will be used to re-evaluate the AoR over the injection phase of the project (Attachment 02: AoR and Corrective Action Plan, 2023). Once LSH INJ1 has been drilled, data gathered during the Pre-operational Testing Program will be used to update the current static model and the computational modeling (Attachment 05: Pre-operational Formation Testing Program, 2023). The updated models will be used to verify or re-evaluate the current AoR, and associated Testing and Monitoring Plan should it be necessary (Attachment 02: AoR and Corrective Action Plan, 2023).

The primary objectives of the LA OBS1 well are to monitor injection zone pressures at a distance from LSH INJ1 and to obtain fluid samples from the well prior to CO_2 breakthrough. The proposed Linden Antilles Deep Observation Well (LA OBS1) is located [redacted] (Figure 3). The location of the deep observation well may move pending the outcome of land negotiations; however, it is expected to remain at approximately the same distance from the injection well. It is estimated that the CO_2 will breakthrough at LA OBS1 between three and five years after injection operations commence based on the computational modeling regardless of the final location given the relatively symmetrical CO_2 plume predictions (Attachment 02: AoR and Corrective Action Plan, 2023).

Fluid samples from the injection zone will allow the project to evaluate changes in aqueous geochemistry during the initial phase of the project. Once the CO_2 breaks through at LA OBS1, the project will use Pulsed Neutron Logging (PNL) to characterize the vertical development of the CO_2 plume over time at a distance from LSH INJ1. The far field pressure measurements will be used to calibrate the computational modeling during the operations phase of the project.

Table 2: Proposed Linden Well Locations - (NAD 1983 UTM Zone 16N).

Well Name	Well Use	X0, feet	Y0, feet	TD, feet	Status
LSH INJ1	Primary CCS Injector well in the Mt. Simon Sandstone	[redacted]			Proposed Wells
LA OBS1	CCS Observation Well				
LR ACZ1	ACZ Monitoring Well				

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Figure 2: Map of Linden Project location, proposed location of LSH INJ1, LA OBS1, LB USDW1, and LR ACZ1 wells, simulated extent of the CO_2 plume 50 years post injection, and AoR based on the delta pressure front after 30 years of injection.

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Figure 3: Time-lapse CO_2 plume development map over 1, 5, 10, 15, 30 (injection end), 40 (10 years post injection) and 80 (50 years post injection). Note the relative stability of the CO_2 plume radius in the PISC phase of the project. Cross section A-A' is shown in Figure 4.

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Figure 4: A-A' cross-section of CO_2 year 80 (50 years post injection) along LSH INJ1 and LA OBS1. Depth in fbsl.

1.4. *Summary of Testing and Monitoring Plan Components*

Operational monitoring serves to ensure all procedures and processes associated with the project are being conducted safely and that well integrity is maintained. Continuously recorded data that will monitor the response of the injection zone include:

- Injection rate and volume,
- Wellhead injection pressure,
- Injection well annulus pressure and fluid volume, and
- Mt. Simon Sandstone pressure and temperature.

The verification monitoring will provide data used to evaluate the vertical and horizontal CO_2 plume development over time and identify any potential CO_2 migration beyond the confining zone. The primary components of the CO_2 plume monitoring consist of PNL in the project wells and time-lapse three-dimensional (3D) surface seismic monitoring. The pressure front development will be monitored with downhole pressure sensors in LSH INJ1 and Linden Antilles Deep Observation Well #1 (LA OBS1) as well as continuous passive seismic monitoring. In addition, the Linden Ralter Above Confining Zone Monitoring Well #1 (LR ACZ1) will provide further verification that the injection zone fluids are being contained below the confining layer through downhole pressure monitoring and fluid sampling in the Ironton-Galesville Sandstones.

The assurance monitoring component of the program will monitor the shallow groundwater aquifers for any indications that injection zone fluids have migrated into the near surface. Fluid samples will be taken from shallow groundwater aquifers on a regular basis to analyze the aqueous geochemistry.

One of the primary goals of the testing and monitoring plan is to continue to demonstrate the activities of this project are safe for the health of the public and environment. In order to help facilitate this demonstration, the Quality Assurance and Surveillance Plan (QASP) (Attachment 11: QASP, 2023) has been developed to ensure the quality of the demonstration methods meet the requirements of the EPA Underground Injection Control (UIC) Program for Class VI wells.

Table 3 shows a summary of the activities, monitoring points, and purpose of each activity as outlined in the Testing and Monitoring Program (Attachment 07: Testing and Monitoring, 2023). The activities are discussed on more detail in sections that follow in this document.

Table 3: Summary of Testing and Monitoring Activities

Activity	Location(s)	Purpose
CO_2 stream analysis	Sensitive, Confidential, or Privileged Information	
CO_2 stream analysis - downstream	[redacted]	Monitor injectate quality and composition
Continuous Recording	[redacted]	
Injection rate	[redacted]	Monitoring injection rate
Injection volume	[redacted]	Calculated injection volume
Wellhead pressure	[redacted]	Monitoring injection pressure Monitoring injection zone pressure Monitoring ACZ
Annular pressure	[redacted]	Monitoring annulus pressure
Annular fluid volume	[redacted]	Monitoring annulus fluid volume changes
Downhole pressure	[redacted]	Monitoring injection zone Monitoring injection zone Monitoring ACZ interval
Downhole temperature	[redacted]	Monitoring injection zone, wellbore integrity
Passive seismic monitoring	[redacted]	Injection zone and confining zone integrity
Well Integrity	[redacted]	
Corrosion monitoring	[redacted]	Monitoring injectate, wellbore integrity
Mechanical integrity (internal)	[redacted]	Wellbore integrity
Mechanical integrity (external)	[redacted]	Wellbore integrity
Cement Evaluation	[redacted]	Wellbore integrity
Plume Tracking	[redacted]	
Pulsed Neutron Log	[redacted]	CO_2 saturation, vertical plume development
Downhole Pressure	[redacted]	Monitoring injection zone pressure, plume monitoring, confining zone integrity
Passive Seismic Monitoring	[redacted]	Injection zone and confining layer integrity
Time-lapse 3D Seismic Data	[redacted]	Indirect measurement of plume development and overburden
Fluid Sampling	[redacted]	
Shallow Ground Water Sampling (Glacial Drift)	[redacted]	Detection of changes in aqueous geochemistry for the shallow USDWs.
Lowermost USDW Sampling (Borden Group)	[redacted]	Detection of changes in the groundwater quality in the lowermost USDW
Above Confining Zone Sampling (Ironton-Galesville)	[redacted]	Detection of changes in aqueous geochemistry above the confining zone.
Injection Zone Monitoring (Mt. Simon Sandstone)	[redacted]	Detection of changes in aqueous geochemistry, and CO_2 saturation in the injection zone.

1.4.1. CO_2 Stream Analysis and Corrosion Monitoring

The chemical composition of the CO_2 stream will be monitored downstream of the final compression unit and upstream of LSH INJ1 (40 CFR 146.90 (a)). Corrosion coupons composed of the same material as the well components and CO_2-delivery pipeline will be placed in the delivery pipeline and analyzed on a quarterly basis for signs of corrosion and loss of mass that may be indicative of future potential well integrity issues (40 CFR 146.90 (c)). If signs of corrosion are identified in the coupons, this may trigger further well integrity testing as outlined in Section 6.2 External Mechanical Integrity Testing.

1.4.2. Injection Well Monitoring

Injection operations will be monitored through a range of continuous, daily, and quarterly techniques as detailed in Attachment 06: Well Operations Plan.

Continuous recording devices will monitor wellhead injection pressure, temperature, and calculated mass flow rate (40 CFR 146.90 (b)). The injection rate will be monitored using an orifice meter prior to entering the wellhead. The calculated injection volumes will, in turn, be used to update the computational models at regular intervals throughout the injection phase of the project (Attachment 02: AoR and Corrective Action Plan, 2023).

The annular pressure between the tubing and the injection casing strings as well as the annular fluid volumes will also be monitored on a continuous basis (40 CFR 146.90 (b)). These data will be linked into a supervisory control and data acquisition (SCADA) system to record the operations data, control injection rates, or initiate system shutdown, if needed.

1.4.3. Mechanical Integrity Testing

In addition to the annular pressure and fluid volume monitoring, the well integrity of LSH INJ1 and LA OBS1 will be monitored using a range of internal and external mechanical integrity evaluation methods. The same methods of mechanical integrity testing (MIT) will be performed on each well.

1.4.3.1. Internal Mechanical Integrity Testing

The regulatory standard for internal MIT is performing an annulus pressure test (APT). This test will be run to regulatory requirements after the well completion to confirm internal integrity as per the Pre-operational Testing Program (Attachment 05: Pre-operational Formation Testing Program, 2023). The APT will only be performed as a baseline measurement. Further details on the APT standards and methods of performing it are provided in Section 6.1.1 Annulus Pressure Testing.

1.4.3.2. External Mechanical Integrity Testing

The external mechanical integrity of the wells will be confirmed through annual temperature and PNL. These logs will be compared to baseline logs to identify any deviations that could indicate CO_2 flow or accumulations behind the casing above the injection zone (40 CFR 146.90 (e)). Further details on these logs and the methods of performing them will be provided in Section 6.2 External Mechanical Integrity Testing.

1.4.4. Pressure and Temperature Monitoring

The bottomhole pressure and temperature will be measured using gauges in LSH INJ1 and LA OBS1 well. The gauges will continuously record these data and transmit them to surface.

LA OBS1 will be located within the area of the predicted 30-year CO_2 plume radius; the CO_2 plume is expected to intersect the well within the first three to five years of injection (Figure 4). This well will allow for pressure and temperature monitoring as well as periodic fluid sampling in the Mt. Simon Sandstone. The variations in the pressure data will be used to calibrate and verify the computational modeling through the pre-operational, injection, and PISC phases of the project (40 CFR 146.90 (g)).

1.4.5. Plume Monitoring

A pressure fall-off test (FOT) will be conducted in the Mt. Simon Sandstone in LSH INJ1 after it is drilled to establish the hydrogeologic characteristics of the injection zone (Attachment 05: Pre-operational Formation Testing Program, 2023). During the injection phase of the project, an FOT will be conducted in LSH INJ1 at least once every five years unless increases in injection pressure indicate a need for a FOT sooner (40 CFR 146.90 (f)). The formation characteristics obtained through the FOT will be compared to the results from previous tests to identify any changes over time, and they will be used to calibrate the computational models.

LA OBS1 will be used to monitor pressure and to collect fluid samples from the injection zone to monitor for changes in the aqueous geochemistry of the formation. It will also be used to verify when the leading edge of the CO_2 plume reaches the observation well.

PNL will be run in the LSH INJ1 and LA OBS1 to monitor CO_2 saturations and vertical plume development adjacent to the wellbores. This logging can also be used to identify accumulations of CO_2 above the confining zone should there be leakage along the wellbore. Once the near wellbore region of LSH INJ1 becomes fully saturated with CO_2, routine logging of the injection interval will be suspended but will continue through the ACZ monitoring interval. Both the pressure and log data will be used to calibrate and verify the computational modeling over the injection and PISC phases of the project.

Beyond the direct measurement techniques that the project will deploy, time-lapse 3D surface seismic data and passive seismic monitoring will be used to monitor the development of the CO_2 plume and the associated pressure front through the injection and PISC phases (40 CFR 146.90 (g)). Time-lapse 3D surface seismic data will be used to qualitatively monitor the CO_2 plume development and calibrate the computational modeling results over time. The time-lapse 3D surface seismic data will also be used to verify CO_2 containment within the injection zone, as any CO_2 accumulations in the overburden would result in seismic anomalies that would differ from the baseline seismic data. Source and received spacing and line intervals, and the resulting trace density will be designed to deliver full offset, full azimuth baseline data of sufficient resolution to image the target horizons.

The passive seismic monitoring array will be used to monitor for seismic events within the AoR that might indicate potential impacts to containment. The monitoring array will be located close to injection well; however, the array can be expanded to cover a larger area over time if required.

1.4.6. Shallow Groundwater Sampling and Monitoring

The shallow groundwater monitoring program will use shallow groundwater wells spatially distributed within the AoR in near-surface groundwater aquifers, and one dedicated groundwater monitoring well that will be drilled into the lowermost USDW in the Borden Group (40 CFR 146.90 (d)). The top of the New Albany Shale is located [redacted] at the project site and is considered the base of the lowermost USDWs based on nearby well data and reports from the Indiana Geological and Water Survey (Attachment 01: Narrative, 2023).

Baseline groundwater samples will be acquired from these wells to help characterize the variations in aqueous geochemistry within the AoR prior to the start of CO_2 injection. In addition to the standard analytes, the groundwater samples will also have their aqueous geochemistry analyzed.

Throughout the injection and PISC phases of the project, the results of the aqueous geochemistry will be compared to the baseline conditions for any indication of CO_2 or brine migration into the shallow groundwater aquifers. If indications of CO_2 or brine are found in the shallow groundwater aquifer, it will trigger the emergency response actions found in the Emergency and Remedial Response Plan (Attachment 10: ERRP, 2023).

1.4.7. Deep Groundwater Sampling and Monitoring

One groundwater monitoring well (LR ACZ1) for the project will be drilled into the Ironton-Galesville Sandstones above the confining zone. Assuming fluid migration from the injection zone is most likely to occur along a wellbore, the LR ACZ1 well will be in close proximity to LSH INJ1 to monitor above the confining layer.

LR ACZ1 will be used to take fluid samples and monitor pressure changes in the Ironton – Galesville Sandstones (40 CFR 146.90 (d)). Injection zone fluid migration past the confining layer and into the ACZ monitoring zone will most likely be identified through pressure changes in the formation. Pressures will be monitored both at the wellhead and downhole in the LR ACZ1 well.

1.4.8. Passive Seismic Monitoring

The project site is located in an area with low rates of natural seismic activity and risk (Attachment 1: Narrative, 2023). It is not expected that natural seismicity will affect the Linden Project. At the Illinois Basin–Decatur Project injection well (CCS1) at the Archer Daniels Midland (ADM) facility in Decatur, IL, CO_2 was injected into the basal Arkose interval of the Mt. Simon Sandstone and generated small seismic events throughout the injection phase of the project CO_2 despite maintaining injection below fracture pressure (Bauer et al., 2016,). Over 80 percent of the induced events were located in the Precambrian basement (Bauer et al., 2019). The Linden Project plans to inject across the entire Mt. Simon Sandstone section and will monitor related seismic activity to assist in managing project risks.

The passive seismic monitoring will be used to accurately determine the locations and magnitudes of injection-induced seismic events with the primary goals:

- To address potential public concerns related to induced seismicity,
- Monitor the spatial extent of the pressure front from the distribution of seismic events around the injection well and as the pressure front expands,
- Identify any activity that may indicate failure of the confining zone and possible containment loss.

A surface-based passive seismic monitoring array will be designed with seismic monitoring stations at a range of azimuths to optimize the accuracy of the event locations and magnitudes. The design of the array will be informed by data collected during the Pre-operational Testing Program (Attachment 05: Pre-operational Formation Testing Program, 2023). This network can be expanded in response to monitoring results or future AoR re-evaluations, if necessary.

1.4.9. General Testing and Monitoring Activity Frequency

Table 4 presents the general schedule and spatial extent for the monitoring activities in the baseline and injection phases of the project based on the current understanding of the site. Refer to the Post Injection Site Care section for discussion on the PISC monitoring plans (Attachment 09: PISC, 2023).

The depth of monitoring and testing ranges will be updated once the data from LSH INJ1 and LA OBS1 has been analyzed and the static model has been updated. Changes to the monitoring schedule may occur over time as the project evolves. Any such changes to the testing and monitoring plan or the PISC will be made in consultation with the UIC Program Director (40 CFR 146.90 (j)).

Table 4: General schedule and spatial extent for the testing and monitoring activities for the Linden Project

Monitoring Activity	Baseline Data Frequency	Injection Phase Frequency*	Location	Depth Range (MD feet)**
Groundwater Monitoring			Sensitive, Confidential, or Privileged Information [redacted]	
Shallow Groundwater Sampling	Quarterly	Biannual (twice/year)		
Fluid Sampling	Biannual (twice/year)	Annual		
Injection Well Monitoring				
Injection Pressure	NA	Continuous		
Injection Temperature	NA	Continuous		
Injection Rate	NA	Continuous		
Injection Volume (Calculated)	NA	Continuous		
Annular Pressure	NA	Continuous		
Annular Fluid Volume	NA	Continuous		
Mechanical Integrity Testing				
Mechanical Integrity Test (MIT) (Internal): Annulus Pressure Test	Once Once	As required		
FOT	Once	Every 5 years		
MIT (External) Temperature Log	Once Once	Annually Annually		
Emergency Shut-down System Test	NA	Annually		
Pressure Monitoring				
Annular Pressure	NA	Continuous		
Wellhead Pressure	NA	Continuous		
Downhole Pressure	NA	Continuous		
CO_2 Stream Analysis				
CO_2 Stream Analysis	Once	Quarterly		
Corrosion Coupon Analysis	NA	Quarterly		

Monitoring Activity	Baseline Data Frequency	Injection Phase Frequency*	Location	Depth Range (MD feet)**
Plume Verification Monitoring				
Pressure and Temperature Sensors	3 months prior to injection Continuous Continuous	Continuous Continuous	Sensitive, Confidential, or Privileged Information [redacted]	[redacted]
PNL	Once Once	Annually Annually	[redacted]	[redacted]
Passive Seismic Monitoring	6 months prior to injection	Continuous	[redacted]	[redacted]
Time-lapse 3D Surface Seismic Data	Once	Every 5 – 10 years	[redacted]	[redacted]

* Minimum frequency displayed in table.
** To be confirmed after well is drilled.
*** Temperature data will not be collected.

1.5. Quality Assurance Procedures

Data quality assurance and surveillance protocols adopted by the project have been designed to facilitate compliance with the requirements specified in 40 CFR 146.90 (k). Quality Assurance (QA) requirements for direct measurements within the injection zone, above the confining zone, and within the lowermost USDW aquifer are described in the Quality Assurance and Safety Plan (Attachment 11: QASP, 2023). These measurements will be performed based on best industry practices and the QA protocols recommended by the service contractors selected to perform the work.

1.6. Reporting Procedures

Linden will report the results of all testing and monitoring activities to the EPA in compliance with the requirements under 40 CFR 146.91. Reports will be submitted every 6 months commencing from the date CO_2 injection operations commence.

2. CO_2 Stream Analysis (40 CFR 146.90 (a))

The project will analyze the CO_2 stream during the injection phase of the project to provide data representative of its chemical characteristics and to meet the requirements of 40 CFR 146.90 (a).

This section describes the measurements and sampling methodologies that will be used to monitor the chemical characteristics of the CO_2 injection stream. Additional details on technical standards, QA/QC policy, sample collection and storage policies, and analytical methods are provided in the QASP (Attachment 11: QASP, 2023).

2.1. Sampling Location and Frequency

Prior to the start of the injection phase, the CO_2 stream from the delivery pipeline will be sampled for analysis to obtain representative CO_2 samples that will serve as a baseline dataset. Once the injection phase commences, samples of the CO_2 injection stream will be collected from the CO_2 delivery pipeline for analysis at the end of each quarter (March, June, September, and December). Quarterly sampling of the CO_2 injection stream should be sufficient to accurately track the composition of the stream.

Section 4.5 of the QASP document (Attachment 11: QASP, 2023) details the quality control mechanisms and activities to be performed should there be a statistically significant variance in an analyte measurement.

2.2. Analytical Parameters

Samples of the injection stream will be collected for chemical analysis of its composition. The samples will be analyzed for CO_2 purity, total hydrocarbons, methane, carbon monoxide (CO), nitrogen oxides (NO_x), nitrogen (N_2), oxygen (O_2), methane, hydrogen sulfide (H_2S), sulphur dioxide (SO_2), acetaldehyde (AA), and ethanol.

Baseline samples of the injection stream will be collected prior to the start of injection and the analytes included for analysis may be expanded depending on the results of those analyses. Gas concentration analyses will be done by a contracted third-party lab. The lab will specialize in gas analyses and routinely perform specialized analyses on CO_2 for industrial clients. Samples of the CO_2 stream will be collected on a quarterly basis for chemical analysis.

2.3. Sampling Method – CO_2 Injection Stream Gases

Gas samples of the CO_2 stream will be obtained to analyze the components present in the injection stream. Samples of the CO_2 stream will be collected between the CO_2 delivery pipeline and the injection wells using a [redacted] sampling port in the flowline. Fittings will be consistent with those used by the contracted third-party laboratory who will be performing the analysis.

The CO_2 stream will flow from the pipeline through an open ball valve, through a pressure reducer (regulator), and into the cylinder. The pressure regulator will reduce the pressure of the CO_2 stream to [redacted] to ensure the CO_2 is in a gaseous state rather than as a super-critical liquid.

Figure 5 provides an example of the sampling procedures used by Atlantic Analytical Company. Cylinders will be purged with sample gas (i.e., CO_2) at least five times prior to sample collection to remove laboratory-added helium gas and ensure a representative sample. The QASP contains more information on sampling methods (Attachment 11: QASP, 2023).

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Figure 5: Atlantic Analytical Laboratory gas sampling instruction sheet.

2.4. Laboratory to be Used, Chain of Custody, and Analysis Procedures

A contracted third-party laboratory will analyze the CO_2 stream samples. The lab will specialize in gas analyses and routinely perform specialized analyses on CO_2 for industrial clients. The contracted laboratory will follow standard sample handling and chain-of custody guidance (EPA 540-R-09-03, or equivalent).

The relevant QASP sections (Attachment 11: QASP, 2023) detail the following:

- Section B.1.a: Laboratory to be used and quality,
- Section B.3.e: Chain of custody,
- Section B.4.a: Analysis procedures.

3. Continuous Recording of Operational Parameters

The project will install and use continuous recording devices to monitor injection pressure; injection rate (and volume [calculated]); the pressure on the annulus; the annulus fluid volume added; and the temperature of the CO_2 stream, as required at 40 CFR 146.88 (e)(1), 146.89 (b), and 146.90 (b). The details are described in the following sections.

3.1. Monitoring Location and Frequency

The project will perform the activities identified in Table 4 to monitor operational parameters and verify internal mechanical integrity of LSH INJ1. All monitoring will take place at the locations and frequencies shown in Table 5. All data recorded on a continuous basis will be connected to the main facility through a SCADA system.

Table 5: Sampling devices, locations, and frequencies for continuous monitoring.

Parameter	Device(s) *	Location	Minimum Sampling Frequency **	Minimum Recording Frequency ***
Wellhead Injection Pressure	Pressure Gauge	Sensitive, Confidential, or Privileged Informa [redacted]	Every 10 seconds	Every 10 seconds
Formation Injection Pressure	Pressure Gauge	[redacted]	Every 10 seconds	Every 10 seconds
Wellhead Injection Temperature	Thermocouple	[redacted]	Every 10 seconds	Every 10 seconds
Formation Temperature	Temperature Sensor	[redacted]	Every 10 seconds	Every 10 seconds
Injection rate	Orifice Meter	[redacted]	Every 10 seconds Every 10 seconds	Every 10 seconds Every 10 seconds
Annular pressure	Pressure Gauge	[redacted]	Every 10 seconds	Every 10 seconds
Annulus fluid volume	Accumulator	[redacted]	Every 1 minutes	Every 1 min

* All calibration standards, methods of conformance, precision, and tolerance parameters are provided for the devices listed in the QASP (Attachment 11: QASP, 2023).

** Sampling frequency refers to how often the monitoring device obtains data from the well for a particular parameter. For example, a recording device might sample a pressure transducer monitoring injection pressure once every two seconds and save this value in memory.

** Recording frequency refers to how often the sampled information gets recorded to digital format (such as a computer hard drive). For example, the data from the injection pressure transducer might be recorded to a hard drive once every minute.

3.2. Monitoring Details

3.2.1. Continuous Recording of Injection Pressure

The CO_2 injection pressure will be monitored on a continuous basis at the wellhead to ensure that injection pressures do not exceed the calculated maximum allowable injection pressure (MAIP), determined, in part, by using 90% of the fracture pressure of the injection zone per 40 CFR 146.88 (a). If the injection pressure exceeds 90% of the injection zone fracture pressure at any point, then the injection process will be automatically shutdown as outlined in the Well Operations Plan (Attachment 06: Well Operations, 2023) (Attachment 06: Well Operations, 2023).

Based on current information, 90% fracture pressure gradient is expected to be [redacted] that results in a maximum allowable bottomhole flowing pressure (BHFP) of [redacted], which is the projected top of the Mt. Simon Sandstone (Attachment 02: AoR and Corrective Action Plan, 2023). This will be re-assessed with the data collected during the Pre-operational Testing Program (Attachment 05: Pre-operational Formation Testing Program, 2023).

The BHFP has been calculated as approximately [redacted] during the first year of normal operations and is anticipated to decline to approximately [redacted] after five years of injection. Based on the calculations and detail provided in the Well Operation Program attachment, the MAIP (at surface) is [redacted] Table 6 summarizes the maximum allowable BHFP after year one (1) and year five (5) as well as the MAIP at surface for LSH INJ1.

Table 6: Summary of BHFP and MAIP for LSH INJ1

Parameter	LSH INJ1
Depth (MD feet)	[redacted]
Maximum Allowable BHFP	[redacted]
Year 1 BHFP	[redacted]
Year 5 BHFP	[redacted]
MAIP (Surface)	[redacted]

Pressure will be continuously monitored by an electronic pressure transducer to ensure that the MAIP is not exceeded during injection operations. This electronic pressure transducer will feed into the SCADA system.

As is noted in the Well Operations section, several assumptions have gone into the calculations for the MAIP (Attachment 06: Well Operations, 2023). To assist with the proper hydrostatic gradient evaluations, permanent downhole gauges will be used. The data gathered from the permanent downhole gauges will help calibrate the surface pressure readings. Current plan is to use these gauges for calibration purposes until sufficient hydrostatic data has been collected. It is noted that these gauges are not considered to be a part of the routine testing and monitoring program, but for gradient calibration and model/simulation verification.

Any anomalies outside of the normal operating specifications may indicate that an issue has occurred within the well, such as a loss of mechanical integrity or blockage in the tubing or may be caused by a change in injection flowrate. Anomalous pressure measurements would trigger the need for further investigation of the cause of the change (40 CFR 146.89 (b)). The wellhead and downhole injection pressures will also be used to calibrate the computational modeling throughout the injection phase and PISC phases of the project.

3.2.2. Continuous Recording of Injection Mass Flow Rate

The mass flow rate of CO_2 injected into the wells will be monitored by an orifice meter. The orifice meter will be placed in the CO_2 delivery line near the injection well. The flow meter will be connected to the SCADA system for continuous monitoring and control of the CO_2 injection rate into the well.

3.2.3. Injection Volume

The injection volume will be calculated for the injection well using an orifice meter. The calculated volume will be used in the computational models to determine storage formation capacity and flow.

3.2.4. Continuous Recording of Annular Pressure

As discussed in the Well Operations Plan (Attachment 06: Well Operations, 2023), the pressure on the annulus between the injection tubing and the long-string casing will be measured by an electronic pressure transducer with analog output that is mounted on the wing valve/annular fluid line connected to the wellhead of LSH INJ1. The transmitter will be connected to the well control system and the SCADA system to regulate the annular pressure.

Annular pressures are expected to vary during normal operations due to atmospheric and CO_2 stream temperature fluctuations; however, the well control system will be designed to maintain the annular pressure [redacted] (Attachment 06: Well Operations, 2023).

In particular, the annular pressure is expected to fluctuate during start-up and shut-in operations as the tubing naturally expands and contracts in response pressure and temperature changes related to CO_2 flow, or lack thereof, in the tubing. Sudden changes in the annular pressure during routine injection operations are a sign of potential tubing or tubing packer integrity issues that will trigger further investigation through mechanical integrity testing.

3.2.5. Continuous Recording of Annulus Fluid Volume

As discussed in the Well Operations Plan (Attachment 06: Well Operations, 2023), the volume of the annulus fluid between the injection tubing and the long-string casing will be measured using the accumulator levels and the brine reservoir level on the well control system. The accumulator and brine reservoir levels will be measured using a level transmitter. The transmitters will be connected to the well control system and to the SCADA system.

Similar to the annular pressure, the annular fluid volume is expected to fluctuate as atmospheric and injection stream temperatures change. These changes are expected to be most dramatic during start-up and shutdown operations. A significant change in the fluid volume in the accumulator or brine reservoir (i.e., fluid is being pumped from the reservoir to the annulus or fluid being pushed out of the annular space) during routine injection operations may be an indication of well integrity problems, as the fluid volumes would normally remain relatively constant, and will require further investigation.

3.2.6. Continuous Recording of CO_2 Stream Temperature

The temperature of the CO_2 injection stream will be continuously measured by an electronic thermocouple. The thermocouple will be mounted in a temperature probe in the CO_2 line at a location close to the pressure transmitter near the wellhead. The transmitter will be electronically connected to the SCADA system.

3.2.7. Bottomhole Pressure and Temperature

Bottomhole pressure and temperature will be monitored prior to and during the injection phase of the project. These data will be used to assist with the calibration of the wellhead pressure measurements to determine the response of the formation to the injected CO_2.

The downhole gauge(s) will be set at the bottom of the injection string, just above the packer, [redacted] and will be programmed to continuously record the pressure and temperature and transmit it to surface.

After the wellhead/injection zone pressure relationship has been defined, the wellhead pressure measurement will be the point of compliance for maintaining injection pressure below 90% of formation fracture pressure as per 40 CFR 146.88 (a). The downhole pressure and temperature data will also be used to calibrate the computational models.

4. Corrosion Monitoring (40 CFR 146.90 (c))

To meet the requirements of 40 CFR 146.90 (c), the project will monitor well materials and components during the operational period for loss of mass, thickness, cracking, pitting, and other signs of corrosion to ensure that the well components meet the minimum standards for material strength and performance (Table 7). This section discusses the measures that will be taken to monitor the corrosion of well materials used in the casing and tubing. For Class VI injection wells, corrosion monitoring of the well materials is required on a quarterly basis (40 CFR 146.90 (c)).

4.1. Monitoring Location and Frequency

Corrosion monitoring of well materials will be conducted using coupons placed in the CO_2 pipeline (Figure 6). The corrosion coupons will be retrieved and analyzed every three months after the date that injection commences.

Sensitive, Confidential, or Privileged Information

[redacted]

Figure 6: Corrosion coupon illustration in pipeline (Cosasco, 2022).

4.2. Sample Description

The coupons will be made from the same materials as the long string casing and tubing (Table 7). Prior to placement of the corrosion coupons in the CO_2 stream, they will be weighed and measured for thickness, width, and length as a baseline measurement.

Table 7: List of equipment coupon with material of construction

Equipment Coupon	Material of Construction
Long String Casing	Sensitive, Confidential, or Privileged Information [redacted]
Injection String	[redacted]
Pipeline	[redacted]
Wellhead	[redacted]
Packer	[redacted]

4.3. Monitoring Details

Corrosion monitoring of well materials will be conducted using coupons placed in the CO_2 pipeline (Figure 6). The coupons will be made of the same materials that are listed in the table above. An example of one such coupon is provided in Figure 7. The coupons will be removed quarterly and assessed for corrosion using American Society for Testing and Materials (ASTM) G1-03: Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens (ASTM, 2017). This method measures the corrosivity of steel to both aqueous and non-aqueous liquid wastes.

Upon removal, coupons will be inspected visually for evidence of corrosion, which may include pitting, cracking, and loss of mass or thickness. The weight and size (thickness, width, length) of the coupons will also be measured and recorded each time they are removed and compared to the baseline measurements. Corrosion rate will be calculated as the weight loss during the exposure period divided by the duration (i.e., weight loss method). If the coupons show evidence of corrosion, LSH INJ1 can be assessed for signs of corrosion using commercially available logging or other inspection tools. The frequency of running these inspection logs will be contingent on the corrosion data from the coupon monitoring program.

Sensitive, Confidential, or Privileged Information

[redacted]

Figure 7: Type of corrosion coupons to be used for corrosion monitoring (Cosasco, 2022).

5. Above Confining Zone Monitoring (40 CFR 146.90 (d))

The project will monitor changes to aqueous geochemistry above the confining zone during the operational period to meet the requirements of 40 CFR 146.90 (d).

5.1. Monitoring Location and Frequency

Table 8 shows the deep ACZ monitoring zone, lowermost USDW, and shallow groundwater monitoring methods, depths, and frequencies. The project will acquire a minimum of one year of shallow groundwater data before injection operations begin. Fluid samples from the Ironton-Galesville Sandstones will be taken twice for analysis prior to the start of injection operations.

Table 8: Schedule for monitoring of pressure and aqueous geochemistry for the LR ACZ1 and shallow groundwater monitoring wells during the pre-operational and injection phases of the project.

Designated Wells	Target Formation	Monitoring Activity	Baseline Frequency	(Minimum) Injection Phase Frequency
Shallow Groundwater Wells TBD, LB USDW1	Unconsolidated Mississippian sediments	Aqueous Geochemistry	Quarterly	Biannual
LR ACZ1	Ironton-Galesville Sandstones	Wellhead Pressure	Continuous	Continuous (Every hour)
		Downhole Pressure	Continuous	Continuous (Every hour)
		Aqueous Geochemistry	Biannual	Annual

Given the thick and continuous nature of the Eau Claire Formation, the highest risk of CO_2 or brine migration out of the injection zone is along the LSH INJ1 and LA OBS1 wellbores that will penetrate the Eau Claire Formation. As such, LR ACZ1 will be drilled near LSH INJ1 to help monitor for any CO_2 leakage or brine migration into the ACZ monitoring zone. Fluids from the deepest ACZ saline formation will be sampled twice prior to the start of CO_2 injection to characterize any natural variability in the fluids in the formation (Table 8).

Migration of CO_2 or brine into the Ironton-Galesville Sandstones will likely first be identified through pressure changes in the formation. An increasing pressure trend in the ACZ monitoring zone could suggest that leakage across the confining zone has occurred. While any increasing trend in pressure will be evaluated, a sustained increase in pressure that deviates more than 5% above baseline values will warrant additional monitoring and inspections to rule out the possibility of fluid leakage out of the injection zone. Such a change in pressure would initiate more frequent fluid sampling and analysis for aqueous geochemistry from the ACZ monitoring zone as well as additional external well integrity investigations in the LSH INJ1 or LA OBS1.

Figure 8 shows the distribution of the groundwater wells within the AoR (Attachment 02: AoR and Corrective Action Plan, 2023). The shallow groundwater monitoring program will include groundwater wells that will be spatially distributed within the AoR (40 CFR 146.90 (d)). Baseline shallow groundwater samples will be collected from shallow groundwater wells within the AoR on a quarterly schedule starting at least one year before injection commencement to characterize the seasonal variations in groundwater quality within the AoR (Table 8).

Sensitive, Confidential, or Privileged Information

[redacted]

Figure 8: Shallow groundwater wells within the AoR.

The accumulation of CO_2 or brine in an overlying aquifer will likely result in changes to the following parameters:

- Aqueous geochemistry parameters such as pH and alkalinity,
- Reaction of cements, mineral surface coatings, and clay particles with the CO_2 will liberate cations and anions into the aqueous phase,
- Carbon isotopes can be used to differentiate between existing CO_2 sources within the AoR and the injected CO_2.

If anomalous changes in the aqueous geochemistry are observed in the ACZ monitoring interval, new samples will be obtained from the affected formation to verify the changes. The frequency with which fluid samples are obtained from each of the zones for analysis will also be increased. If the injected CO_2 has a unique isotopic signature from the existing isotopes in the ACZ monitoring interval, a new round of samples will be collected for isotopic analysis from the affected formation. Anomalous changes may also trigger the need for additional well integrity testing in both LSH INJ1 and LA OBS1 to ensure that no well integrity issues have developed since the last set of external mechanical integrity tests (Section 6.2). Stable isotopes from the shallow groundwater samples will only be analyzed if anomalies are found in the ACZ monitoring interval.

A combination of anomalous pressure, geochemical, and well integrity testing results may result in the decision to acquire a time-lapse surface seismic survey to determine the size of a potential leakage accumulation. Further details on any remedial or emergency response are detailed in the ERRP portion of this permit application (Attachment 10: ERRP, 2023).

5.2. Analytical Parameters

Table 9 details the full suite of analytes that will be used to establish the baseline conditions from LA OBS1, LR ACZ1, and the shallow groundwater monitoring wells. Once the project has established baseline conditions, it may reduce monitoring to a subset of analytes that are most likely to change as a result of interactions with CO_2; however, no changes would be implemented without consultation with the UIC Program Director. During the injection phase of the project, fluids from these wells will be sampled biannually to identify any changes to parameters aqueous geochemistry.

Table 9: Summary of analytical and field parameters for groundwater samples

Parameters	Analytical Methods *
Cations: Ca, Fe, K, Mg, Na, Si	EPA 6010B
Cations: Al, Sb, As, Ba, Cd, Cr, Cu, Pb, Mn, Hg, Se, Tl	EPA 200.8, EPA 245.1
Anions: Br, Cl, F, NO_3, and SO_4	EPA 300.0
Alkalinity	SM 2320B
Total Dissolved Solids (TDS)	SM 2540C
Total Organic Carbon (TOC)	SM 5310C
Dissolved Inorganic Carbon (DIC)	SM 5310C
Total and Dissolved CO_2	ASTM D513-06B
Stable Isotopes of δ13C	Isotope Ratio Mass Spectrometry **
pH	Field with multi-probe system
Conductivity/Resistivity	Field with multi-probe system
Temperature	Field with multi-probe system

* An equivalent method may be employed with the prior approval of the UIC Program Director.
** Gas evolution technique by Atekwana and Krishnamurthy (1998) with modifications made by Hackley et al. (2007)

Changes in these parameters during the injection phase of the project may provide an indication of CO_2 or brine movement above the confining layer. While pH and alkalinity may be indicators of CO_2 migration above the confining zone, the dissolved inorganic carbon analysis would provide direct evidence of CO_2 migration into these formations. $\delta^{13}C$ values (of dissolved inorganic carbon) could provide an indication of fluid or CO_2 migration into the ACZ monitoring zone and may also provide information about the origin of any migrating fluids.

The relative benefit of each analytical measurement will be evaluated throughout the design and initial injection testing phase of the project to identify the analytes best suited to meeting project monitoring objectives under site-specific conditions. If some analytical measurements are shown to be of limited use, they will be removed from the analyte list and not carried forward through the operational phases of the project. Any modification to the parameter list in Table 9 will be made in consultation with the UIC Program Director.

Currently, there are no plans to use tracers during operations; however, as the monitoring plan is designed to be adaptive as project risks evolve over time and may be re-assessed later.

5.3. Monitoring and Sampling Methods

Pressure in the ACZ monitoring zone will be monitored from the wellhead and downhole. The gauges will record and transmit data to the SCADA system once every 10 seconds. The downhole gauges will be installed in the LR ACZ well when the well is completed. The wellhead gauges will be installed at least three months prior to any injection to ensure that a sufficient baseline is established.

For ACZ fluid sampling, a bailer system will be used to collect the water samples. Prior to sample collection the well will be flushed to remove stagnant water from the well and ensure representative water is collected from the formation. The fluid removed from the well will be monitored for field parameters that are listed in Table 9. Once these parameters stabilize, it will be an indication that representative formation fluid is in the well at the time the sample is collected.

Preservation/preparation methods, container type, and holding times for the analyte classes are presented in the QASP section of this application (Attachment 11: QASP, 2023).

5.4. Laboratory to be Used/Chain of Custody Procedures

The geochemical analyses and the isotopic analyses will be performed by contracted third-party laboratories that meet the standards and guidelines set forth in the QASP. Samples will be tracked using appropriately formatted chain-of-custody forms (Attachment 11: QASP, 2023).

6. Mechanical Integrity Testing

6.1. Internal Mechanical Integrity Testing

Internal mechanical integrity testing (MIT) refers to the testing of the integrity of the seals within and between the: injection string, the long casing string, the packer, and the wellhead. The quality of these seals can be confirmed with an annulus pressure test (APT) and annular pressure monitoring. Both methods will be used during the injection phase of this project to monitor and confirm internal mechanical integrity. Table 10 presents the details for conducting the annular pressure MIT and the annular pressure monitoring.

Table 10: Internal mechanical integrity monitoring details

Testing/Monitoring Method	Frequency	Location of Monitoring	Parameters Measured
Annular Pressure Test	After completion	[redacted]	Pressure
Annular Pressure Monitoring	Continuous		Pressure, temperature, annular fluid volume
*No continuous annular fluid volume monitoring			

An APT will be performed after the initial well completion. It is noted that the annulus will be filled with a non-corrosive fluid with some additives.

6.1.1. Annulus Pressure Testing (40 CFR 146.89(a))

The APT will be performed to exhibit internal mechanical integrity any time a component of the internal seals, detailed above, are broken or altered. The test will be performed consistent with approved and accepted guidance and regulations. This is consistent with CFR 146.89 (a). In addition, an APT will be performed following an emergency shut-in due to a high-high or low-low annulus alarm should the cause of the alarm not be easily correlated to a change in temperature.

The APT will then be performed by pressuring up the annulus after the well has reached thermal equilibrium. Once this has occurred, the annulus will be pressured [redacted] A calibrated digital gauge will be installed on the annulus, and the pressure will be monitored for a period no less than 60 minutes. The following procedure will be followed for all APTs that will be run:

1. Ensure well is in thermal equilibrium. Thermal equilibrium will be assumed under the following circumstances:
   a. Injection has not occurred for approximately 24 hours, or sufficient data indicates the wellbore temperature is static. The scenario constitutes a static APT.
   b. Injection is occurring at a constant rate (±5%), often referred to as a dynamic APT.
2. Install calibrated digital gauge on the casing-tubing annulus. Note initial pressures.
3. Increase annulus pressure to [redacted]
   a. Ensure to note the fluid level in the system prior to increasing the annulus pressure.

4. Disconnect annulus system and ensure the annulus is isolated.
5. Monitor the annulus and tubing pressure for a period of one-hour, taking readings every 10-minutes.
6. Once the test has concluded, reconnect the annulus system.
7. Blow the pressure down to the normal operating pressure.
8. Note the fluid level in the system.

6.1.2. Annulus Pressure Monitoring

In addition to the APT, the annular pressure will be continuously monitored throughout the operational period in conjunction with the annular pressure monitoring and control system to ensure internal mechanical integrity. Once injection operations commence, injection pressure, annular pressure, and annular fluid volumes will be monitored continuously in order to ensure that internal well integrity and proper annular pressure is maintained (Attachment 06: Well Operations, 2023).

If a change in the annular pressure or annular fluid volume indicates a change that was not a result of temperature or injection rate alteration, the cause of the change will be investigated (Attachment 06: Well Operations, 2023). Note that changes in the temperature of the injection stream can result in changes in the temperature of the annular space, leading to variations in annular pressure. Initial investigations would likely look at correlations between the temperature of the injection stream and the variations in annular pressure.

6.2. External Mechanical Integrity Testing (40 CFR 146.90 (e))

The project will conduct external MIT annually to meet the requirements of 146.89(c) and 146.90(e).

6.2.1. Testing Methodology and Frequency

External mechanical integrity refers to the absence of fluid movement through channels between the long casing string and the borehole or the intermediate casing string. Migration of fluids through this zone could result in contamination of USDWs; therefore, the external integrity of LSH INJ1 and LA OBS1 will be confirmed throughout the injection phase of the project. External MIT activities will occur annually.

This project plans to use temperature to ensure external mechanical integrity. It is noted that the practice of running temperature to ensure external mechanical integrity is a generally accepted method used in Class I and II wells across multiple EPA regions. Radioactive tracer (RAT) logs can be run contingently to ensure external mechanical integrity, if required.

Table 11 shows the logs to be run to display external mechanical integrity, as well as the frequency with which they will be run and the depth range they will be run over.

Table 11: External mechanical integrity tests

Test	Well	Depth Range (MD ft)	Schedule
Temperature Log	LSH INJ1	Sensitive, Confidential, or Privileged Information [redacted]	Annually
	LA OBS1	[redacted]	Annually
Radioactive Tracer Log	LSH INJ1	[redacted]	If required

It is important to note that while PNL is not planned to be a direct method of displaying external mechanical integrity, it can be used to identify accumulations of CO_2 adjacent to the wellbore in intervals above the Mt. Simon Sandstone.

6.2.1.1. Temperature Logging

Temperature logging is used to establish a temperature profile of the well and make year to year comparisons to determine if any unexpected variations are present. Multiple temperature logging runs are acquired during each event to capture the temperature decay over a six-hour period (Table 12).

Temperature logs will be run using the same tool assembly as is presented in the RAT logging Section 6.2.1.2. The well will be shut-in, and a baseline temperature log will be run as per the schedule in Table 12. This will allow for four temperature curves to be plotted for each year that temperature logs will be performed. Temperature logs will be acquired from the bottom up.

Table 12: Temperature logging schedule for well integrity

Temperature Logging Run	Time Increment from Shut-in (hours)
Baseline	Shut-in
Second	1
Third	3
Fourth	6

6.2.1.2. Radioactive Tracer Logging

The primary purpose of RAT logging is to verify the absence of pathways along the wellbore for the upward migration of injection zone fluids. RAT logging will be performed in accordance with federal and state guidance if it is available.

RAT logs will be run while fluid is actively being injected into the well. As such, pressure, temperature, and rate data will be collected as part of the logging activities and reporting.

A RAT logging tool will be run on the same string as a gamma ray (GR), casing collar locator (CCL), and temperature tool. Following is a summary of the general testing events:

1. Run baseline GR log across the zone of interest.

2. Run 5-minute statistical (stat) checks on the tool. The stat checks will be conducted within intervals having known low and high GR signatures to ensure the tool is operating properly.

3. Run tracer chase sequence. A tracer will be ejected [redacted], after which the tool will chase the tracer down the injection string and into the cased-hole interval by performing successive downward passes through the well. Multiple passes will be made over the perforated interval to ensure that all the tracer has exited the tubing and passed into the Mt. Simon Sandstone.

4. Run time-drive sequence. A tracer will be ejected [redacted]. After which the tool will be moved to just above the packer. The tool will record the GR measurements at the set depth for a minimum of 30-minutes. During this time, the tracer will be observed passing the tool and never have any upward movement.

5. Run final GR log across the zone of interest.

This sequence of logs will allow for investigation into any potential upward pathways for fluid migration out of the injection interval present during injection.

6.2.2. Testing Details

The data from each annual logging event will be compared to the baseline log to determine if there are any inconsistencies between the logs. If inconsistencies appear, the cause of the deviations will be determined, and additional logs will be performed over the entire depth of the well to substantiate results of the MIT logging.

7. Pressure Fall-off Testing (40 CFR 146.90 (f))

The project will perform pressure FOTs during the injection phase as described below to meet the requirements of 40 CFR 146.90(f).

Pressure fall-off testing involves the measurement and analysis of pressure data from a well after it has been shut-in. FOT tests provide the following information:

- Confirmation of reservoir properties such as flow capacity (KH), which is used to derive average permeability,
- Formation damage (skin) near the well bore, which can be used to diagnose the need for well remediation,
- Changes in injection zone performance over time, such as long-term pressure build-up in the injection zone.

Average injection zone pressure can be used to calibrate computational modeling predictions of injection zone pressure to verify that the operation is responding as modeled/predicted.

7.1. Testing Location and Frequency

Fall-off tests will be run every five years on LSH INJ1 during injection operations. An initial FOT will be run as part of the pre-operational testing to be performed on the well. The permanent downhole pressure gauges set above the packer will be used for the FOT. Surface monitoring equipment will be used to monitor injection data for the test.

7.2. Testing Details

To begin the FOT, a constant rate injection period will be used for a minimum period of 24-hours. The rate will be kept within ±5% during this period and will be at a rate that is representative of the injection rate for normal operations.

Following this constant rate injection period, injection will cease, and the well will be shut-in at the wellhead. Pressure will be monitored for a period to be no longer than the constant rate injection period. Following the shut-in period, the well will be restarted, and routine injection operations will resume.

Surface monitoring equipment will be used to record the injection data. This test can be performed as a function of routine injection operations and will prevent any additional shut-in of the well other than what is necessary for the test. The downhole pressure data will be collected, and pressure transient analysis (PTA) will be performed on the data. Analysis of the test data will be completed using PTA techniques that are consistent with guidance for conducting pressure fall-off tests.

8. CO_2 Plume and Pressure Front Tracking (40 CFR 146.90 (g))

The project will employ direct and indirect methods to track the extent of the CO2 plume and the presence or absence of elevated pressure during the operation period to meet the requirements of 40 CFR 146.90 (g).

8.1. Plume Monitoring Location and Frequency

Table 13 presents the methods that the project will use to monitor the position of the CO_2 plume; this includes the activities, locations, and frequencies the project will employ. The parameters to be analyzed as part of fluid sampling in the injection zone and associated analytical methods are presented in Table 9. Quality assurance procedures for these methods are presented in Attachment 11: QASP.

Table 13: CO_2 plume monitoring activities

Target Formation	Monitoring Activity	Monitoring Location(s)	Spatial Coverage	Frequency
Direct Plume Monitoring				
Mt. Simon Sandstone	Fluid Sampling	Sensitive, Confidential, or Privileged Information [redacted]		Annually
	PNL			Annually until fully saturated with CO_2 Annually
	Downhole Pressure			Continuous

Indirect Plume Monitoring			
Entire Interval	Time-lapse 3D Surface Seismic Data	Sensitive, Confidential, or Privileged Information [redacted]	Every five (5) to ten (10) years as appropriate
Entire Interval	Passive Seismic Monitoring	[redacted]	Continuous

Fluid samples will be obtained for analysis from the Mt. Simon Sandstone during the initial well completion and pre-operational testing program (Attachment 05: Pre-operational Formation Testing Program, 2023). The final sampling interval in the Mt. Simon Sandstone will be determined after the well has been drilled and the well logs have been analyzed. The CO_2 plume is expected to intersect LA OBS1 approximately three to five years after injection commences. Once free phase CO_2 breaks through at LA OBS1, the project will stop taking fluid samples from the Mt Simon Sandstone.

Baseline PNL logs will be acquired in LSH INJ1, LA OBS1, and LR ACZ1 prior to the start of injection operations. Once injection starts, PNL logs will be acquired in LSH INJ1 and LA OBS1 once each year. PNL logs may be acquired in the ACZ wells as a contingency monitoring action.

A baseline 3D surface seismic survey will be acquired prior to the start of injection operations. Subsequent time-lapse 3D surface seismic surveys will be acquired every five (5) to ten (10) years after injection operations commence.

At this time, no continuous CO_2 plume monitoring has been planned for the project. Likewise, no phased or adaptive monitoring has been planned for the project in terms of expanding the monitoring network. However, if during the reassessment of the AoR during the injection phase of the project, the AoR is shown to have grown, the Testing and Monitoring Plan will be reassessed (Attachment 02: AoR and Corrective Action Plan, 2023).

8.2. Plume Monitoring Details

As CO_2 is injected into the Mt. Simon Sandstone, the geochemistry of the fluids in the formation are expected to change. Geochemical modelling will be used to predict the geochemical changes to the Mt. Simon Sandstone fluids once data from the pre-operational testing program has been collected (Attachment 05: Pre-operational Formation Testing Program, 2023).

The results of the geochemical will be delivered in the form of lab reports. Sections 5.2 and 5.3 of this document detail the sampling procedures and the analytical and field parameters that will be used for the fluid sampling. Table 9 summarizes the analytical and field parameters for the fluid sampling. Details on the methods, containers, and preparation methods for the fluid sampling can be found in the QASP section (Attachment 11: QASP, 2023). The project will stop taking fluid samples from the Mt. Simon Sandstone once free phase CO_2 is encountered at the sampling ports.

The PNL logs will be received as LAS files and interpreted products that can be imported into the static model. This logging data will be used to monitor the distribution and saturation of CO_2 adjacent to the wellbores in LSH INJ1 and LA OBS1. The logs will be acquired through the Mt. Simon Sandstone as well to confirm the absence of CO_2 accumulations along the wellbore above the confining zone in the ACZ monitoring zone. Technical details on the logging tools can be found in the QASP section (Attachment 11: QASP, 2023).

Surface seismic data is delivered in a variety of formats including acquisition and processing reports and SEG-Y data files from a variety of points in the processing flow. The data will be processed using industry standard workflows for noise attenuation, demultiple, pre-stack migration, and time-lapse analysis. For time-lapse analysis, an assessment will be provided on the differences between the baseline and time-lapse surveys. The injection of CO_2 and expansion of the plume is expected to change the acoustic impedance and travel times of the seismic waves through the injection zone, and these changes will be used to track CO_2 plume development over time. The time-lapse surface seismic data will also be examined for changes that may suggest that CO_2 has migrated past the confining zone and into the overlying formation(s).

The results of the geochemical analyses, PNL, and time-lapse 3D surface seismic data will be integrated to evaluate the CO_2 plume development over time. The logging and time-lapse 3D surface seismic data can be incorporated into the static model for comparison to the computational modeling predictions at different points in time. The monitoring data can be used to constrain the computational modeling results and produce more accurate plume predictions over the course of the project. The logging data will be used to calibrate the computational modeling on a yearly basis and provide information on the vertical and horizontal plume development. It will also provide more detailed and direct measurement of CO_2 saturations than indirect seismic methods. The time-lapse 3D surface seismic data will be used to update the models every five (5) to ten years. If the CO_2 plume monitoring data diverges significantly from the modelled plume predictions, it may result in a reassessment of the AoR (Attachment 02: AoR and Corrective Action Plan, 2023).

8.3. Pressure Front Monitoring Location and Frequency

Table 14 presents the methods that Vault Alliance CCS, LP (VA) will use to monitor the position of the pressure front; this includes the activities, locations, and frequencies that the project will employ. Quality assurance procedures for these methods have been presented in the QASP (Attachment 11: QASP, 2023).

Table 14: Pressure plume monitoring activities

Target Formation	Monitoring Activity	Monitoring Location(s)	Spatial Coverage	Frequency
Direct Pressure-Front Monitoring		Sensitive, Confidential, or Privileged Information		
Mt. Simon Sandstone	Downhole Pressure Monitoring	[redacted]		Continuous
Indirect Pressure-Front Monitoring				
Entire Interval	Passive Seismic Monitoring			Continuous

The downhole pressure sensors will be programmed to measure and record pressure and temperature readings every 10 seconds The pressure sensor in the injection well will be set above the packer [redacted]. The project will start recording pressures in the injection zone in the injection well and the deep observation well before injection operations commence.

Passive seismic data will also be recorded on a continuous basis. These data will be sent to a cloud-based service via a cellular connection for data processing and archive. Baseline seismic data will be acquired for four to six months prior to the start in injection operations. No phased or adaptive monitoring has been planned for the project in terms of expanding the monitoring network. However, if during the reassessment of the AoR during the injection phase of the project, the AoR is shown to have grown, the Testing and Monitoring Plan will be reassessed (Attachment 02: AoR and Corrective Action Plan, 2023).

8.4. Pressure Front Monitoring Details

Sensors will be placed on the tubing string of LSH INJ1, LA OBS1, and LR ACZ1 to monitor the pressures. Temperature will also be collected on LSH INJ1. The gauges will collect and transmit data to surface continuously. Refer to the QASP for technical information on the potential pressure gauges (Attachment 11: QASP, 2023).

The pressure data and temperature data for LSH INJ1 will be stored as time-stamped data. It is expected that the pressure in the injection zone will begin to increase when injection operations begin. This data will be used to calibrate the computational modeling results over the injection and PISC phases of the project. Calibrating the computational model with pressure and temperature data from the injection zone will lead to more accurate predictions of pressure plume behavior over time. The AoR and Corrective Action Plan further discusses how the pressure and temperature data will be used to calibrate the computational modeling, and how it might be used to trigger an early reassessment of the AoR (Attachment 02: AoR and Corrective Action Plan, 2023).

The proposed seismic monitoring array will have a minimum of five stations. One station will be located adjacent to LSH INJ1, and four stations will be distributed within the AoR. The objective of the array will be to monitor induced seismic events within the pressure front with a magnitude of completeness (Mc) of 1.5 or greater. The physical locations of these stations will be optimized through a design process once the data from LSH INJ1 and LA OBS1 have been analyzed. The local array will be complemented with the addition of any relevant regional seismometer stations that are available through the Incorporated Research Institutions for Seismology (IRIS) to aid in positioning events from outside the AoR.

Each standalone station is expected to consist of a seismometer, digitizer, solar with battery backup, and a cell modem/antenna. The seismometer will be buried [redacted] Triggered data will be processed to provide magnitude and location error ellipsoids on a real-time basis and results will be reviewed by a data processor and event data can be received by the project daily. Automatic notifications will be sent for events over a certain size. The event locations will be incorporated into the static model.

9. References

Attachment 01: Narrative, 2023: Linden.

Attachment 02: AoR and Corrective Action Plan, 2023: Linden.

Attachment 05: Pre-operational Formation Testing Program, 2023: Linden.

Attachment 06: Well Operations, 2023: Linden.

Attachment 07: Testing and Monitoring, 2023: Linden.

Attachment 09: PISC, 2023: Linden.

Attachment 10: ERRP, 2023: Linden.

Attachment 11: QASP, 2023: Linden.

Bauer, R. A., M. Carney, and R. J. Finley, 2016, Overview of microseismic response to CO2 injection into the Mt. Simon saline reservoir at the Illinois Basin-Decatur Project: International Journal of Greenhouse Gas Control, v. 54, p. 378–388, doi:10.1016/j.ijggc.2015.12.015.

Bauer, R., W. R, S. Greenberg, and S. Whittaker, 2019, Illinois Basin - Decatur Project: Geophysics and Geosequestration, p. 339–369.