Class VI Injection Well Application

Contains proprietary business information.

Attachment 06: Testing And Monitoring Plan

40 CFR 146.90

Beargrass Project
Wabash County, Indiana

26 July 2024

Project Information

Project Name: Beargrass

Project Operator: Vault GSL CCS Holdings LP

Project Contact: Jennifer Jacobs, Project Manager
Vault GSL CCS Holdings LP
1125-17th Street, Suite 1275
Denver, Colorado 80202
Email: jenn@vault4401.com
Phone: 713-930-4401

Beargrass Project Injection Well 1 (PNM INJ1) Location:
Wabash County, Indiana
Latitude: 40.94407° N
Longitude: -85.77952° W

Table of Contents

List of Figures

List of Tables

List of Acronyms

25Cr80	25-Chrome L-80
AA	acetaldehyde
ACZ	above confining zone
AoR	Area of Review
APT	annulus pressure test
ASTM	American Society of Testing and Materials
fbgl	feet below ground level
BHFP	bottomhole flowing pressure
CO	carbon monoxide
CO_2	carbon dioxide
CH_4	methane
EPA	Environmental Protection Agency
ERRP	Emergency and Remedial Response Plan
FOT	fall-off test
GR	Gamma Ray
H_2S	hydrogen sulfide
MAIP	maximum allowable injection pressure
Mc	magnitude of completeness
MD	measured depth
MIT	mechanical integrity test
N_2	nitrogen
N/A	not applicable
NO_x	nitrogen oxides
O_2	oxygen
PBI	proprietary business information
PISC	Post-injection Site Care and Site Closure
PNL	Pulsed Neutron Logging
PNM ACZ1	Beargrass Project Above Confining Zone Monitoring Well 1
PNM INJ1	Beargrass Project Injection Well 1
PNM OBS1	Beargrass Project Deep Observation Well 1
PNM USDW1	Beargrass Project USDW Monitoring Well 1
psi	pounds per square inch
QA	Quality Assurance
QASP	Quality Assurance and Surveillance Plan
SCADA	supervisory control and data acquisition
SM	standard method
SO_2	sulfur dioxide
TBD	to be determined
TD	total depth
UIC	Underground Injection Control
USDW	underground source of drinking water

1. Overall Strategy and Approach for Testing and Monitoring

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

1.1. Testing and Monitoring Plan Strategy

The Beargrass Project uses a risk-based Testing and Monitoring Plan that includes operational, verification, and environmental assurance components that meet the regulatory requirements of 40 CFR 146.90. This Testing and Monitoring Plan 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 Beargrass Project Injection Well 1 (PNM INJ1) is operating as planned while maintaining mechanical integrity,
- Acquisition of data to validate and calibrate the models used to predict the distribution of carbon dioxide (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.

The monitoring activities fall within three categories based on project objectives: operational, verification, and assurance monitoring (Table 1).

- ***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 zone. The CO_2 plume and pressure front 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 post injection phases of the project's lifecycle.

- ***Assurance monitoring*** is performed at surface and near-surface (i.e., soil, shallow groundwater, USDWs, etc.) to monitor for any changes from baseline sample data that might indicate CO_2 or injection zone fluid migration towards surface.

The three monitoring categories encompass:

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

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

Claimed as PBI

[redacted]

1.2. Storage Complex

A site-specific stratigraphic chart of geologic formations present is shown in Figure 1. The specific intervals to be monitored are as follows:

- Mt. Simon Sandstone (injection zone),
- Ironton-Galesville Sandstones (Above Confining Zone [ACZ] interval),
- Pleasant Mills (lowermost USDW),
- Shallow groundwater.

Age	Group	Nomenclature	Lithology	Use
Quaternary	Quaternary	Undifferentiated		USDW
Silurian	Salina	Wabash/Salina		
		Pleasant Mills		Lowermost USDW
Ordovician	Maquoketa	Maquoketa/Kope		Secondary Confining
	Galena	Trenton		
	Black River	Black River		
	Ancell	Joachim,Dutchtown/ Gull River, Glenwood		Secondary Confining
	Knox	Shakopee		
		Oneota		
Cambrian		Potosi		
	Potsdam	Davis		Secondary Confining
		Franconia		
		Ironton-Galesville		ACZ monitoring
		Eau Claire Shale		Primary Confining
		Eau Claire Silt		Secondary Storage
		Mt. Simon Sandstone	Upper B-cap Lower	Injection
Precambrian	Precambrian			

Basement Carbonate Sandstone Siltstone Shale Sediment Knox Unconformity

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 identify the proposed well locations for the project. Figure 2 shows the predicted CO_2 plume extent 50-years post injection, the pressure front at the end of 12 years of injection, and the project AoR. Figure 3 and Figure 4 illustrate the map view and a cross section of the modeled CO_2 plume development up to 50-years post injection. The CO_2 plume and pressure front computational modeling 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, 2024). Once PNM 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 Testing Program, 2024). 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, 2024).

The primary objective of the Beargrass Project Deep Observation Well (PNM OBS1) is to monitor injection zone pressures at a distance from PNM INJ1. The project intends to locate the deep observation well such that the CO_2 plume will intersect the well between four and eight years after the injection operations commence based on the computational modeling. The proposed location of PNM OBS1 is approximately 2,416 feet to the west-southwest of PNM INJ1 (Figure 3). The location of the deep observation well may move pending the outcome of land negotiations; however, it is expected to remain at a similar distance from the injection well.

The project will use Pulsed Neutron Logging (PNL) to characterize the vertical development of the CO_2 plume over time at a distance from PNM INJ1. The far-field pressure measurements will be used to calibrate the computational modeling during the operations phase of the project.

Claimed as PBI

[redacted]

Claimed as PBI

[redacted]

Claimed as PBI

[redacted]

Claimed as PBI

[redacted]

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 confirms 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.

Claimed as PBI

[redacted]

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 that 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 10: Quality Assurance and Surveillance Plan, 2024) has been developed to ensure that the quality of the demonstration methods meet the requirements of the Environmental Protection Agency (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 Plan. The activities are discussed in more detail in sections that follow in this document.

Claimed as PBI

[redacted]

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 PNM 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 1.4.3.2 External Mechanical Integrity Testing (40 CFR 146.90 (e)).

1.4.2. Injection Well Monitoring

Injection operations will be monitored through a range of continuous, daily, and quarterly techniques. 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, 2024).

The annular pressure between the tubing and the injection casing strings will also be monitored on a continuous basis (40 CFR 146.90 (b)), and annular fluid volumes will be measured indirectly. 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 PNM INJ1 and PNM OBS1 will be monitored using a range of internal and external mechanical integrity evaluation methods.

1.4.3.1. Internal Mechanical Integrity Testing

The regulatory standard for an internal mechanical integrity test (MIT) is performing an annulus pressure test (APT). This test will be run to regulatory requirements after the initial well completion to confirm internal integrity as per the Pre-operational Testing Program (Attachment 05: Pre-operational Testing Program, 2024). The APT will be performed after the initial completion and after subsequent workovers. Further details on the APT standards and methods of performing it are provided in Section 6.1.1 Annulus Pressure Testing .

Should tubing not be present within one of the project monitoring wells, a suitable alternative method will be used to establish internal mechanical integrity. One such example is a casing pressure test, which can be run using similar test parameters as the APT. As with the APT, the casing pressure test will only be performed as an initial baseline measurement and will be performed on an as needed basis during the injection phase of the project.

1.4.3.2. External Mechanical Integrity Testing

The external mechanical integrity of the injection well will be confirmed through annual temperature decay logs. 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 (40 CFR 146.90 (e)).

1.4.4. Pressure and Temperature Monitoring

Claimed as PBI

[redacted]

1.4.5. CO_2 Plume and Pressure Front Monitoring

Claimed as PBI

[redacted]

Claimed as PBI

[redacted]

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 lowermost USDW monitoring well that will be drilled into the Pleasant Mills Formation (40 CFR 146.90 (d)). The top of the Pleasant Mills Formation is located at 291 feet below ground level at the project site and is considered the lowermost USDW based on nearby well data and reports from the Indiana Geological and Water Survey (Attachment 01: Narrative, 2024). 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.

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 injection zone fluid migration into the shallow groundwater aquifers. If indications of CO_2 or injection zone fluid are found in the shallow groundwater aquifer, it will trigger the emergency response actions found in the Emergency and Remedial Response Plan (ERRP) (Attachment 09: Emergency and Remedial Response Plan, 2024).

1.4.7. Deep Groundwater Sampling and Monitoring

Claimed as PBI

[redacted]

1.4.8. Passive Seismic Monitoring

The project site is located in an area with low rates of natural seismic activity and risk (Attachment 01: Narrative, 2024). It is not expected that natural seismicity will affect the Beargrass Project. The Beargrass Project plans to inject in the Mt. Simon Sandstone and will monitor related seismic activity to assist in the management of project risks.

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

- To address potential public concerns related to induced seismicity,
- Qualitatively monitor the spatial extent of the pressure front based on 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.

Claimed as PBI [redacted]

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 PISC section for discussion on the PISC monitoring plans (Attachment 08: Post-injection Site Care and Site Closure, 2024).

The depth of testing and monitoring ranges will be updated once the data from PNM INJ1 and PNM 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 will be made in consultation with the UIC Program Director (40 CFR 146.90 (j)).

Claimed as PBI

[redacted]

Claimed as PBI

[redacted]

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 are described in the QASP (Attachment 10: Quality Assurance and Surveillance Plan, 2024). These measurements will be performed based on industry best practices and the QA protocols recommended by the service contractors selected to perform the work.

1.6. Reporting Procedures

The Beargrass Project 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 six months 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/Quality control policy, sample collection and storage policies, and analytical methods are provided in the QASP (Attachment 10: Quality Assurance and Surveillance Plan, 2024).

2.1. Sampling Location and Frequency

Prior to the start of the injection phase, the post-compression CO_2 stream 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 will be sufficient to accurately track the composition of the stream.

Section 4.5 of the QASP document (Attachment 10: Quality Assurance and Surveillance Plan, 2024) 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 (CH_4), carbon monoxide (CO), nitrogen oxides (NO_x), nitrogen (N_2), oxygen (O_2), hydrogen sulfide (H_2S), sulfur 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 ¼-inch 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, a pressure reducer (regulator), and into the cylinder. The pressure regulator will reduce the pressure of the CO_2 stream to approximately 250 pound-force per square inch (psi) 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 Laboratory. 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 10: Quality Assurance and Surveillance Plan, 2024).

Introduction

Atlantic Analytical Laboratory (AAL) provides pre-cleaned and conditioned stainless steel and sulfur-inerted sampling cylinders as a convenience to our customers. Rental cylinders are available in a variety of sizes, including 75cc, 300cc, 500cc, and 1 liter. All cylinders are DOT rated for **1,800 psig** service, and are equipped with a burst-disc type relief valve set to approximately this pressure. All cylinders are dual ended, with **1/4" NPT** valve port fittings. **Cylinders are normally shipped with approximately 10 psig UHP grade helium backfill gas to prevent atmospheric contamination during shipment.** Cylinders can be shipped under vacuum upon request.

Safety

Before sampling, review all MSDS information related to the gases present. Always wear safety glasses, protective gloves, and other necessary safety equipment. Sampling cylinders are only to be used by personnel trained in handling pressurized gases. For safety, always assume any cylinder or gas line contains the maximum amount of pressure possible in the system. Whenever possible, ensure that the sampling cylinder outlet port is attached to an appropriate vent line to avoid a potentially hazardous buildup of the gas being sampled, especially for oxygen and flammable gases. **Refer to the back of this page for a diagram of a typical sampling setup.**

- **DO NOT** sample toxic, corrosive, pyrophoric, or extremely reactive gases with these cylinders.
- **DO NOT** sample cryogenic or liquefied gases using these instructions; instead, refer to separate instructions available from AAL for proper sampling techniques for these gases.
- **DO NOT EXCEED the MAXIMUM 1,800 PSIG fill pressure.** If the relief valve burst disc ruptures, the cylinder cannot be used for sampling - return to AAL immediately for repairs, cleaning, and recertification.

Equipment

Sampling cylinder, ¼" NPT brass end cap, ¼" NPT brass plug, ID tag.

Sampling Procedure

1) Remove the brass cylinder end cap and plug and store them in a clean, secure location.
2) Loosely connect the inlet valve of the sampling cylinder to the gas source valve.
3) Carefully open the gas source valve and purge the connecting fittings of air - then tighten these fittings. Keep the gas source valve open until step 11.
4) Carefully open the cylinder inlet valve to allow the sample gas to fill the cylinder.
5) Close the cylinder inlet valve. Do not over tighten, as this may damage the valve seat and cause leakage.
6) Open the cylinder outlet valve, and allow a majority the cylinder gas to vent. **DO NOT** blow down completely to atmospheric pressure, as this may cause outside contaminants to diffuse into the cylinder.
7) Close the cylinder outlet valve.
8) Repeat steps 4 - 7 a minimum of 5 times to ensure the cylinder has been purged of all fill gas and conditioned with the sample gas.
9) Open the cylinder inlet valve and partially open the cylinder outlet valve to allow the sample gas to flow through the cylinder for at least 2 minutes.
10) Close the cylinder outlet valve and wait at least 30 seconds for the cylinder to fully pressurize.
11) Close both the cylinder inlet and gas source valves - then carefully disconnect the cylinder. Beware of excess gas pressure trapped between the two valves which may release suddenly when disconnecting the cylinder.
12) Apply new teflon tape to the NPT threads on the inlet valve of the cylinder and the brass outlet plug and securely cap both ends of the cylinder. **DO NOT** over tighten fittings or thread damage may result.
13) Record all sample data on the cylinder ID tag **– please do not affix labels to the cylinder body.**
14) Package the cylinder in a DOT/IATA approved shipping box or container and insert a completed AAL "Analytical Testing Request" form. Follow all applicable shipping regulations including affixing the proper sample UN designation, shipping name, hazard labels, and identification of the sample contents on all courier paperwork.
15) Ship the sample to AAL via an express air (if eligible) or qualified ground courier as soon as possible.

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 10: Quality Assurance and Surveillance Plan, 2024) detail the following:

- I.10.4.3.5 *Sample Chain of Custody*,
- I.10.4.4.1 *Analytical Standard Operating 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; 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 PNM 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) [1]	Location	Minimum Sampling Frequency [2]	Minimum Recording Frequency [3]
Wellhead injection pressure	Pressure gauge	Wellhead	Every 10 seconds	Every 10 seconds
Formation injection pressure	Pressure gauge	Above packer (TBD)	Every 10 seconds	Every 10 seconds
Wellhead injection temperature	Thermocouple	Wellhead	Every 10 seconds	Every 10 seconds
Formation temperature	Temperature sensor	Above packer (TBD)	Every 10 seconds	Every 10 seconds
Injection rate	Orifice meter	Inlet and outlet to pipeline	Every 10 seconds Every 10 seconds	Every 10 seconds Every 10 seconds
Annular pressure	Pressure gauge	Wellhead	Every 10 seconds	Every 10 seconds
Annulus fluid volume[4]	Annulus Pressure Gauge	Wellhead	Every 10 seconds	Every 10 seconds

[1] All calibration standards, methods of conformance, precision, and tolerance parameters are provided for the devices listed in the QASP (Attachment 10: Quality Assurance and Surveillance Plan, 2024).

[2] 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.

[3] 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.

[4] Annular fluid volume will be monitored continuously indirectly through changes in annulus pressure. Any fluid additions or offtake will be measured.

3.2. Monitoring Details

Claimed as PBI

[redacted]

Claimed as PBI

[redacted]

3.2.2. Continuous Recording of Injection Mass Flow Rate

The mass flow rate of CO_2 injected into the well will be calculated using the flowrate measured 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

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 wellhead. 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 around 100 psi (Attachment 01: Narrative, 2024).

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

The volume of the annulus fluid between the injection tubing and the long-string casing will be measured continuously by changes in annulus pressure. Any fluid additions or offtake will be measured.

Similar to the annular pressure, the annular fluid volume is expected to fluctuate as atmospheric and wellbore temperatures change. These changes are expected to be most dramatic during start-up and shutdown operations. A significant change in the fluid pressure and volume 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 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 set at approximately [redacted] feet 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.

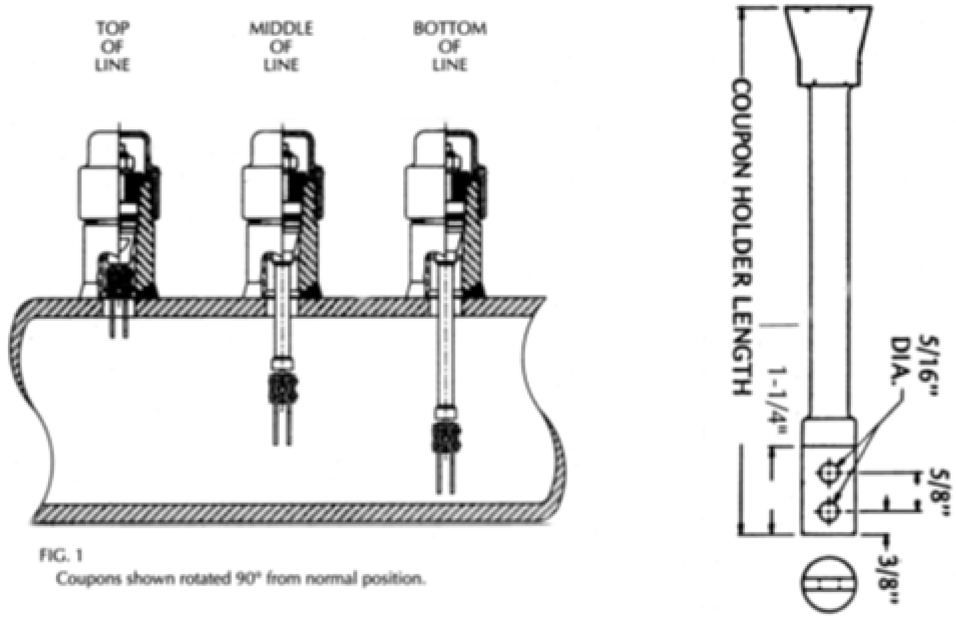

Figure 6: Corrosion coupon illustration in pipeline (Cosasco, 2022).

4.2. Sample Description

The coupons will be made from the same materials as the long string casing, injection tubing, and other components in regular contact with the CO_2 stream (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.

Claimed as PBI

[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 Table 7. 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

G1-03, 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 significant corrosion, PNM INJ1 can be assessed for signs of corrosion using commercially available logging or other inspection tools. The inspection log frequency will be contingent on the corrosion data from the coupon monitoring program.

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 once for analysis prior to the start of injection operations.

Claimed as PBI

[redacted]

Given the thick and continuous nature of the Eau Claire Shale, the highest risk of CO_2 or brine migration out of the injection zone is along the PNM INJ1 and PNM OBS1 wellbores that will penetrate the Eau Claire Shale. As such, PNM ACZ1 will be drilled near PNM INJ1 where injection zone pressures are the highest to help monitor for any CO_2 leakage or brine migration into the ACZ monitoring zone. Fluids from the Ironton-Galesville Sandstones will be sampled once 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 two-sigma 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 PNM INJ1 or PNM OBS1.

Figure 8 shows the distribution of the shallow groundwater wells within the AoR (Attachment 02: AoR and Corrective Action Plan, 2024). 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 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).

Claimed as PBI

[redacted]

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 that will liberate cations and anions into the aqueous phase,
- Carbon isotopes which may 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 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 PNM INJ1 and/ or PNM OBS1 to ensure that no well integrity issues have developed since the last set of external mechanical integrity tests (Section 1.4.3 Mechanical Integrity Testing).

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 09: Emergency and Remedial Response Plan, 2024).

5.2. Analytical Parameters

Table 9 details the full suite of analytes that will be used to establish the baseline conditions from the injection zone, PNM ACZ1, and the shallow groundwater monitoring wells. Once the project has established baseline conditions, monitoring may be reduced to a smaller 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 the shallow groundwater monitoring wells will be sampled biannually, while PNM ACZ1 will be sampled annually, to identify any changes to parameters aqueous geochemistry.

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

Parameters	Analytical Methods [1]
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	Standard Method (SM) 2320B
Total dissolved solids	SM 2540C
Total Organic Carbon	SM 5310C
Dissolved Inorganic Carbon	SM 5310C
Total and Dissolved CO_2	ASTM D513-06B
Stable Isotopes of δ13C	Isotope Ratio Mass Spectrometry [2]
pH	Field with multi-probe system
Conductivity/Resistivity	Field with multi-probe system
Temperature	Field with multi-probe system

[1] An equivalent method may be employed with the prior approval of the UIC Program Director.
[2] 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, the monitoring plan is designed to be adaptive as project risks evolve over time, and this 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 gauges. The gauges will record and transmit data to the SCADA system once every 10 seconds. The wellhead and downhole gauges will be installed in the ACZ well when the well is completed.

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 to ensure a 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, the representative formation fluid in the well will be collected.

Preservation/preparation methods, container type, and holding times for the analyte classes are presented in the QASP section of this application (Attachment 10: Quality Assurance and Surveillance Plan, 2024).

5.4. Laboratory to be Used/Chain of Custody Procedures

The geochemical 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 10: Quality Assurance and Surveillance Plan, 2024).

6. Mechanical Integrity Testing

6.1. Internal Mechanical Integrity Testing

Internal 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 APT and annular pressure monitoring. Both methods will be used during the injection phase of this project to monitor and confirm internal mechanical integrity after well workovers and as a contingent action during injection operations. Table 10 presents the details for conducting the annular pressure MIT and the annular pressure monitoring.

Claimed as PBI

[redacted]

An APT, or suitable alternate, 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

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

Prior to beginning the APT, a calibrated digital gauge will be installed on the annulus, The APT will begin by pressuring up the annulus to 1,500 psi after the well has reached thermal equilibrium. The pressure will be monitored for a period of no less than 60 minutes.

The following procedure will be followed for all APTs that will be run:

1. Install a calibrated digital gauge on the casing-tubing annulus. Note initial pressures on the tubing and annulus.
2. Ensure the 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.

3. Increase annulus pressure to 1,500 psi.

   a. Ensure to note the fluid level in the system prior to increasing the annulus pressure.
4. Disconnect the 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 are maintained (Attachment 01: Narrative, 2024).

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. Note that changes in the temperature of the injection stream can result in changes in the temperature of the annular space and lead 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 an 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 PNM INJ1 will be confirmed throughout the injection phase of the project. External MIT activities will occur annually.

This project plans to use temperature logs to display external mechanical integrity. It is noted that the practice of running temperature logs to display 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 as a contingency 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.

Claimed as PBI

[redacted]

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 response profile to injection 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 Section 6.2.1.2 *Radioactive Tracer Logging*. 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, and temperature tool. The 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 at least 300 feet above the packer, after which the tool will chase the tracer down the injection string and into the Mt. Simon Sandstone by performing successive downward passes through the well 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 at least 300 feet above the packer. 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 the 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

FOTs will be run every five years on PNM INJ1 during injection operations. An initial FOT will be run as part of the pre-operational testing to be performed on the well (Attachment 05: Pre-operational Testing Program, 2024). The permanent downhole pressure gauges set above the packer will be used to collect bottomhole data for the FOT.

7.2. Testing Details

To begin the FOT, a constant rate injection period lasting a minimum of 24 hours will be carried out. 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 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. Pressure transient analysis (PTA) will be performed on the collected test 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 CO_2 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. CO_2 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 and the associated analytical methods are presented in Table 9. Quality assurance procedures for these methods are presented in (Attachment 10: Quality Assurance and Surveillance Plan, 2024).

Claimed as PBI

[redacted]

8.2. CO_2 Plume Monitoring Details

Claimed as PBI

[redacted]

Claimed as PBI

[redacted]

8.3. Pressure Front Monitoring Location and Frequency

Table 14 presents the methods that the Beargrass Project 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 10: Quality Assurance and Surveillance Plan, 2024).

Claimed as PBI

[redacted]

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. The project will start continuously recording pressures in the injection zone in the injection well and the deep observation well when 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 passive seismic data will be acquired for six months prior to the start of 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, 2024).

8.4. Pressure Front Monitoring Details

Claimed as PBI

[redacted]

9. References

ASTM G1-03, 2017, ASTM G1-03: Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens, Annual Book of ASTM Standards: ASTM International, p. 9.

Atekwana, E. A., and R. V. Krishnamurthy, 1998, Seasonal variations of dissolved inorganic carbon and δ13C of surface waters: application of a modified gas evolution technique: Journal of Hydrology, v. 205, no. 3, p. 265–278, doi:10.1016/S0022-1694(98)00080-8.

Attachment 01: Narrative, 2024, Underground Injection Control Class VI Permit Application: Beargrass Project.

Attachment 02: AoR and Corrective Action Plan, 2024, Underground Injection Control Class VI Permit Application: Beargrass Project.

Attachment 05: Pre-operational Testing Program, 2024, Underground Injection Control Class VI Permit Application: Beargrass Project.

Attachment 08: Post-injection Site Care and Site Closure, 2024, Underground Injection Control Class VI Permit Application: Beargrass Project.

Attachment 09: Emergency and Remedial Response Plan, 2024, Underground Injection Control Class VI Permit Application: Beargrass Project.

Attachment 10: Quality Assurance and Surveillance Plan, 2024, Underground Injection Control Class VI Permit Application: Beargrass Project.

Cosasco, 2022, Retrieved from https://www.cosasco.com/.

Hackley, K., S. Panno, H.-H. Hwang, and W. Kelly, 2007, Groundwater Quality of Springs and Wells of the Sinkhole plain in Southwestern Illinois: Determination of Dominant Sources of Nitrate: ISGS Circular, v. 570.