Class VI Injection Well Application

Attachment 05: Pre-operational Testing Program
40 CFR 146.82(a)(8), 146.87

Aster Project
Madison County, Indiana

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Project Information

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Aster Project Injection Well 1 (AST INJ1) Location:
Madison County, Indiana
Latitude: 40.30026° N
Longitude: -85.65565° W

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List of Acronyms

ACZ	above confining zone
APT	annulus pressure test
AST ACZ1	Aster Project Above Confining Zone Monitoring Well 1
AST INJ1	Aster Project Injection Well 1
AST OBS1	Aster Project Deep Observation Well 1
AST USDW1	Aster Project USDW Monitoring Well 1
bpm	barrels per minute
BHA	bottomhole assembly
CO_2	carbon dioxide
CBL-VDL	cement bond log-variable density log
DST	drill stem test
EPA	Environmental Protection Agency
FOT	fall-off test
fbgl	feet below ground level
MIT	mechanical integrity test
PNL	pulsed neutron log
psi	pounds per square inch
RAT	radioactive tracer
SRT	step-rate test
TBD	to be determined
TDS	total dissolved solids
US	United States
USDW	underground source of drinking water

1. Introduction

This document details the proposed Pre-operational Testing Program that will be implemented to characterize the chemical and physical features of the lithology at the Aster Project site. The formations of note include, but are not limited to, the following:

- Mt. Simon Sandstone (injection zone),
- Eau Claire Shale (confining zone),
- Knox Supergroup (above confining zone [ACZ] monitoring interval).

The Pre-operational Testing Program laid out in this document is designed to meet the testing requirements of Title 40 of the U.S. Code of Federal Regulations Section 146.87 (40 CFR 146.87), and the well construction requirements of 40 CFR 146.86. Attachment 01: Narrative (2024) details the construction plan for the Aster Project Injection Well 1 (AST INJ1). This document details how the depth, thickness, mineralogy, lithology, porosity, permeability, and geomechanical information of the injection zone, confining zone, and other relevant geologic formations will be determined and verified (Figure 1, Figure 2, and Figure 3). The Pre-operational Testing Program includes a combination of logging, coring, fluid sampling, and formation hydrogeologic testing that will be completed when the project wells are drilled. The wells to be drilled for the Aster Project include:

- AST INJ1
- Aster Project Deep Observation Well 1 (AST OBS1)
- Aster Project Above Confining Zone Monitoring Well 1 (AST ACZ1)

Vault GSL CCS Holdings LP will notify the United States (US) Environmental Protection Agency (EPA) 30 days ahead of the planned spud date for each of the project wells of the intent to drill, log, and test each well as well as a schedule of well logging and testing activities. An updated timeframe will be provided at least 48 hours in advance to serve as notice and provide the opportunity to witness the relevant tests or logs.

AST OBS1 is expected to be the first well drilled with the timing dependent on the anticipated receipt of the Class VI injection well permit. A minimal logging suite will be run to establish depths and thicknesses of formations at the site. This initial logging suite will be used to identify zones suitable for core acquisition and well testing. A more extensive logging suite is planned for AST INJ1 to assist with characterization of the main formations of interest. AST OBS1 will allow the project to determine the behavior of various intervals in the Knox Supergroup, such as the Potosi Formation, which have caused lost circulation issues for other wells in the region. A porous and permeable interval within the Knox Supergroup will be identified and established as the ACZ monitoring interval for the project.

The lowermost underground source of drinking water (USDW) at the Aster Project site is in the Pleasant Mills Formation, and its base is the top of the Maquoketa Group (Attachment 01: Narrative, 2024) as displayed in Figure 1. The US EPA defines a USDW as an aquifer with less than 10,000 total dissolved solids (TDS), measured in milligrams per litre.

Fluid samples will be collected and used to complete the baseline aqueous geochemistry for the lowermost USDW and the ACZ monitoring intervals for future comparison to monitoring data collected after injection operations begin.

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		ACZ Monitoring
		Oneota		
Cambrian		Potosi		
	Potsdam	Davis		Secondary Confining
		Eau Claire Shale		Primary Confining
		Eau Claire Silt		Secondary Storage
		Mt. Simon Sandstone	Upper B-cap Lower	Injection
Precambrian	Precambrian			

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

After the data acquired in AST OBS1, AST ACZ1, and AST INJ1 has been analyzed, a Pre-operational Narrative will be submitted to the US EPA that will provide the new data and the updated static and computational models that will incorporate the data from the testing program.

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2. Pre-injection Testing Plan – Injection Well (146.87 (a))

The following tests and logs will be conducted when AST INJ1 is drilled, the casing is installed and cemented, and the hydrogeologic properties are tested in accordance with 40 CFR 146.87(a), (b), (c), and (d). The tests and procedures are described in the section below.

AST INJ1 will be the carbon dioxide (CO_2) injection well, and the primary well used to collect pre-operational data that will include but not be limited to:

- Wireline logs, core, fluid samples, and well test data,
- Well integrity data that will ensure that the project wells will not serve as a conduit for CO_2 or injection zone fluid migration to the overlying USDWs.

2.1. Deviation Checks (146.87 (a)(1))

Deviation surveys will be obtained as the wells are drilled to determine the wellbore path from the surface to the total depth of the well. A wireline survey tool will be used to measure the inclination. The tool has an electronic timer that is set at the surface to allow enough time to run the tool in the drill pipe to the desired depth. Following the set time, the tool will be removed from the well, and the results will be reviewed prior to the resumption of drilling activity.

An alternative way to measure these deviation surveys is to place a measurement while drilling tool on the bottomhole assembly (BHA) just above the drill bit. This tool records the inclination (deviation) and azimuth (direction) of the tool, and then transmits this information to surface in real-time.

Hole deviation will be maintained at less than five degrees, as the planned maximum allowable deviation in the well is five degrees. If necessary, the wellbore will be steered back to an acceptable deviation with directional tools such as a downhole motor or rotary steerable system added to the BHA. Surveys will be taken at the frequency shown in Table 1. In general, a survey will be performed every 500 feet while drilling unless deviation of the borehole becomes apparent.

Should the deviation increase, more frequent surveys will be performed, and remedial actions will occur as necessary to bring the well within specification. More frequent surveys will also be performed while drilling through zones that are likely to cause the bit to "walk" creating a greater risk for deviation. Surveys will be repeated at the intervals specified in Table 1 until the wellbore has less than 1 degree of inclination.

Table 1: AST INJ1 deviation survey frequencies to be taken.

Range of Deviation	Frequency of Survey
<1 degree	1 survey per every 500 feet of hole
>1 degree, but < 2 degrees	1 survey per every 250 feet of hole
>2 degrees	1 survey per every 100 feet of hole

2.2. Tests and Logs

2.2.1. Tests and Logs Performed During Drilling

2.2.1.1. Well Logging

Table 2 and Figure 4 summarize the type and purpose of each well logs that the Aster Project proposes to acquire in the surface, intermediate (contingent), and long string casing segments of the well.

In addition to the well logs listed in Table 2, the project may run other specialty well logs over the injection zone and confining interval to further characterize these formations. Specialty logs may include, but are not limited to, elemental capture spectroscopy, dipole sonic in multiple modes, or zero offset vertical seismic profiles.

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2.2.1.2. AST INJ1 Well Core Program (146.87 (b)(d))

After AST OBS1 has been drilled, the well logs will be analyzed and used to pick the optimal intervals to obtain core from the confining zone and the injection zone in AST INJ1. Up to 60 feet of core will be acquired in both the Eau Claire Shale and the Mt. Simon Sandstone. Table 3 summarizes the plans for whole core acquisition from AST INJ1.

Table 3: Whole core collection plan.

Core Type	Target Interval Measured Depth (feet)	Formation	Core Size
Whole Core	Up to 60 feet	Eau Claire Shale	4-inch
Whole Core	Up to 60 feet	Mt. Simon Sandstone	4-inch
Sidewall Core	Contingency	As Needed	1.5-inch
Note: Whole core plugs will be taken from the whole core at regular intervals. Sidewall core collection will be contingent on the results of the well logging and the success of the whole core acquisition.			

Sidewall core intervals will be used as contingency to infill zones where the project would like to acquire additional data or in zones where the project was not able to obtain the desired whole core intervals. Sidewall cores collected will provide a comprehensive set of routine rock property data to calibrate geophysical wireline logs and to supplement formation property data where whole core data are not available.

Additional core will be collected if:

- Interpretated well data indicates that additional data are needed to meet Class VI permit requirements.
- As required by the Director.

Core samples from AST INJ1 will provide information on geologic properties in the immediate area. The laboratory-derived core measurements will be integrated with wireline logs and used for petrophysical calibration. The integrated dataset will then be correlated with wireline logs from offset wells to support the correlation and confirmation of stratigraphy and rock properties.

Formal core plans and numbers of cores to be used for each analysis will be provided once finalized with a coring contractor prior to well installation (Table 4).

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2.2.2. Tests and Logs Performed During and After Casing Installation (146.87 (a)(2), (3))

2.2.2.1. Well Logging

Table 5 summarizes the cased hole well logs that will be acquired after casing is set and cemented for each well section. The bottom of the surface casing will be set at approximately [redacted] feet below ground level (fbgl) as per Attachment 01: Narrative (2024). Intermediate casing will be installed in the injection well in the event that lost circulation zones are encountered in the Knox Supergroup when the well is drilled. As such, logging runs in the intermediate casing string have been labeled as contingency (Attachment 01: Narrative, 2024). Long string casing will be set at approximately [redacted] approximately [redacted] feet into the Lower Mt. Simon Sandstone (Attachment 01: Narrative, 2024).

[redacted]

2.2.2.2. *Fluid Sampling and Analysis (146.87 (b – d))*

The characterization of injection zone fluids will be based on analysis of fluid samples acquired from AST INJ1. These samples will be collected through swabbing, drill stem tests (DSTs), or downhole pumps and will provide information on the baseline aqueous geochemistry of the injection zone fluids. The fluid samples will be analyzed for TDS and major analytes (Table 6). The static fluid level of the injection zone will also be established in AST INJ1.

Table 6: 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	SM 2320B
TDS	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 Underground Injection Control Program Director.

[2] Gas evolution technique by Atekwana and Krishnamurthy (1998) with modifications made by Hackley et al. (2007)

2.2.2.3. Step-Rate Testing (146.87 (d)(1))

A step-rate test (SRT) will be performed on the injection zone interval through the analysis of the pressure response to increases in injection rates. This is done to determine:

- Fracture opening pressure (to determine the fracture gradient),
- Fracture propagation pressure,
- Fracture closure pressure.

Injection at each of the rates will be performed on AST INJ1 for the same period as detailed in the high-level procedure below. A formal procedure will be provided to the US EPA prior to the running of the SRT.

1. Record downhole static pressure and temperature for a minimum of one hour.
2. Rig-up pump truck, ensure sufficient volume of fluid is present at location to begin testing.
3. Pressure test lines above maximum anticipated operating pressure, but below equipment rating.
4. Begin SRT.
    a. Pump first step of test at first desired rate (e.g., 0.5 barrels per minute [bpm]) for a defined time (e.g., 0.5 hours).
    b. After the first step is completed, increase rate to next step (e.g., 1.0 bpm) for the same defined step time (0.5 hours).
    c. Repeat until the end of the test.
5. Shut-in well at the wing valve(s). Record the time of shut-in, the rate prior to shut-in and the instantaneous shut-in pressure.
6. Rig-down pump truck.
7. Monitor pressure falloff for minimum of 24-hours.

The data from this test will be analyzed using appropriate analysis software, and the results will be included in the post installation reporting. Gauge calibration records will also be provided at this time.

The results from the SRT will be combined with the results from the core analyses and log data to determine the direction and magnitude of the three principal components of the stress field as well as the fracture gradient. Additional data may include, but are not limited to, triaxial compressive strength tests of core samples as well as dipole sonic and image logs.

2.2.3. Demonstration of Mechanical Integrity (146.87 (a)(4))

Table 7 summarizes the mechanical integrity tests (MITs) that will be used to demonstrate the integrity of the injection well.

Table 7: Pre-operational mechanical integrity testing schedule for the injection well.

Class VI Rule Citation	Rule Description	Test Description	Program Period
40 CFR 146.89(a)(1)	MIT - internal	Annulus pressure test (APT)	Following initial completion
40 CFR 146.87(a)(4)	MIT - external	Temperature log	Following initial completion
40 CFR 146.87(a)(4)	MIT - external	Radioactive tracer (RAT) log	Following initial completion (if needed)

Vault GSL CCS Holdings LP will notify the US EPA least 30 days prior to conducting the test and provide a detailed description of the testing procedure. Notice and the opportunity to witness these tests/logs shall be provided to the US EPA at least 48 hours in advance of a given test/log.

2.2.3.1. Internal Mechanical Integrity Testing (146.87 (a)(4)(i))

Internal mechanical integrity refers to the integrity of the seal between the long string casing, injection tubing, wellhead, and packer as well as the integrity of the individual components. In this subsection, the annulus refers to the casing-tubing annulus. The effectiveness of this seal can be confirmed with an annulus pressure test (APT) and annular pressure monitoring.

Internal mechanical integrity will be demonstrated by way of an APT as is standard for Underground Injection Control wells. A baseline APT will be performed to 1,500 pounds per square inch (psi) after the tubing, packer, downhole equipment, and the wellhead have been installed as outlined in Attachment 01: Narrative (2024). 1,500 psi has been designated as the maximum operating pressure for the annulus.

In addition to the APT, the tubing will be inspected as it is being installed to monitor the tubing for corrosion. Once injection commences, injection pressure, annular pressure, and annular fluid volumes will be monitored continuously to ensure internal well integrity and proper annular pressure is maintained (Attachment 06: Testing and Monitoring, 2024).

2.2.3.2. External Mechanical Integrity Testing (146.87 (a)(4)(ii – iv))

External mechanical integrity refers to the absence of fluid movement through channels in the cement between the long string casing and the borehole. The external integrity of AST INJ1 and AST OBS1 will be monitored through the life of the project wells. The external mechanical integrity will be monitored on the schedule provided in Attachment 06: Testing and Monitoring (2024).

Generally accepted methods for evaluating external mechanical integrity include:

- Temperature or noise log,
- Oxygen-activation logging or radioactive tracer (RAT) logging (during operation),
- Or other logs the operator deems appropriate.

After completion, a baseline temperature log will be run from surface to the bottom of the long string casing to establish the initial temperature conditions along the well. Note that in cases where a static temperature log or temperature profile have been referenced, only the baseline temperature log will be collected. Temperature logging will be performed at regular intervals during the injection phase of the project based on the schedule provided in the Testing and Monitoring Plan (Attachment 06: Testing and Monitoring, 2024). The results of these logs will be compared to the baseline log to determine if anomalies that suggest CO_2 is migrating up the wellbore are present.

If the temperature logging data suggest that an issue with external well integrity exists, a RAT log will be performed to evaluate external well integrity with greater sensitivity. In addition to the baseline temperature log, a cement bond log-variable density log (CBL-VDL), and advanced ultrasonic cement evaluation log will be run across the entire long string casing after completion of the injection well to confirm that the casing string was properly cemented (Table 5). CBL-VDLs are recorded with sonic tools that detect the bond of the casing and formation to the cement and identify potential damage or channels in the cement. Ultrasonic tools provide higher accuracies and resolutions for cement evaluation than CBL-VDLs.

3. Pre-injection Testing Plan – Deep Observation Well AST OBS1 (146.87 (a))

AST OBS1 is expected to be the first well drilled for the project. The well will be logged to establish depths to formation tops, fluid sampling zones, and potential coring intervals in the injection well. The deep observation well will also be used to identify a porous and permeable interval within the Knox Supergroup that will provide a suitable ACZ monitoring interval. Intermediate casing will be installed in the well in the event that lost circulation zones are encountered in the Knox Supergroup when the well is drilled, as such logging runs in the intermediate casing string have been labeled as contingency.

3.1. Deviation Checks (146.87 (a)(1))

Deviation surveys will be obtained as the observation well is drilled, following the procedure outlined in Section 2.1 *Deviation Checks* (146.87 (a)(1)).

3.2. Tests and Logs

3.2.1. Tests and Logs Performed During Drilling

Table 8 summarizes the open hole logs that will be acquired before casing has been set for the surface, intermediate, and long string casing, as well as the purpose of each well log.

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3.2.2. Tests and Logs Performed During and After Casing Installation

Table 9 summarizes the cased hole logs that will be run after casing has been set for the surface, intermediate, and long string casing, as well as the purpose of each well log.

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3.2.3. Demonstration of Mechanical Integrity (146.87 (a)(4))

Table 10 summarizes the MITs to be performed on the deep observation well after installation and prior to commencing CO_2 injection operations:

Table 10: Pre-operational mechanical integrity testing schedule for the deep observation well

Test Name	Test Description	Program Period
MIT - Internal	APT or casing pressure test	Following initial completion
MIT - External	CBL-VDL	During initial completion

Notice and the opportunity to witness the test/log shall be provided to the US EPA at least 48 hours in advance of a given test/log.

4. Pre-injection Testing Plan – ACZ Monitoring Well AST ACZ1 (146.87 (a))

4.1. Deviation Checks (146.87 (a)(1))

Deviation surveys will be obtained as the ACZ well is drilled and will follow the procedure outlined in Section 2.1 Deviation Checks (146.87 (a)(1)).

4.2. Tests and Logs

4.2.1. Tests and Logs Performed During Drilling

No tests or logs are planned in AST ACZ1 during drilling.

4.2.2. Tests and Logs Performed During and After Casing Installation

AST ACZ1 will be drilled after AST OBS1. Cased hole logs will be acquired in AST ACZ1 to assess cement integrity and obtain baseline pulsed neutron logs for future reference (Table 11).

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The characterization of ACZ monitoring zone fluids will be based on analysis of fluid samples acquired from AST ACZ1. These samples will be collected through swabbing, DSTs, or downhole pumps and will provide information on the baseline aqueous geochemistry of the ACZ monitoring zone fluids for comparison to future monitoring data. The fluid samples will be analyzed for TDS and major analytes (Table 6). The static fluid level of the ACZ monitoring zone will also be established in AST ACZ1.

4.2.3. Demonstration of Mechanical Integrity (146.87 (a)(4))

Table 12 summarizes the MITs to be performed on the ACZ monitoring well after installation and prior to commencing CO_2 injection operations:

Table 12: Pre-operational mechanical integrity testing schedule for the ACZ monitoring well

Test Name	Test Description	Program Period
MIT - Internal	Casing pressure test	Following initial completion, prior to perforating ACZ interval
MIT - External	CBL-VDL	During initial completion

Notice and the opportunity to witness the test/log shall be provided to the US EPA at least 48 hours in advance of a given test/log.

5. APT Procedures for Injection Well

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.

The APT will be performed to demonstrate internal mechanical integrity following the initial completion of the well. The test will be performed consistent with approved and accepted guidance and regulations (CFR 146.89 (b)).

The APT will be performed by pressuring up the annulus to 1,500 psi after the well has reached thermal equilibrium. 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 (or some other form of fluid adjustment or alteration, such as filling the annulus) has not occurred for approximately 24 hours, or sufficient data indicates the wellbore temperature is static. The scenario constitutes a static APT.
2. Install calibrated digital gauge on the casing-tubing annulus. Note initial pressures.
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 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. Internal Mechanical Integrity Testing for Deep Observation Well AST OBS1

Should the decision be made to complete and install tubing in the AST OBS1 well, an APT will be performed after initial well completion (Section 5 *APT Procedures*). In the event that tubing is not installed in the AST OBS1 well, a casing pressure test will be performed after the initial well completion. This test will provide an indication of the integrity of the casing-wellhead seal and casing integrity. The procedure outlined below will be followed to perform the test:

1. Install calibrated digital gauge on the wellhead. Note initial pressures.
2. Increase pressure to 1,500 psi.
3. Monitor the pressure for a period of one-hour, taking readings every 10-minutes.
4. Once the test has concluded, blow the pressure down to the pre-test pressure.

7. Internal Mechanical Integrity Testing for Monitoring Well AST ACZ1

A casing pressure test will be performed on the ACZ monitoring well after initial well completion and prior to the perforation of the well. This test will provide an indication of the integrity of the casing-wellhead seal and casing integrity.

8. Pressure Fall-Off Test Procedures (146.87 (e))

A pressure fall-off test (FOT) will be run on AST INJ1. The purpose of this test is to further characterize the hydrogeologic characteristics of the injection zone. During this test, fluid will be injected at a constant rate for a predetermined length of time, after which the well will be shut in, and the pressure monitored for an equal period of time.

The data from this test will be evaluated using rate superposition analysis to determine injection zone information such as permeability, skin factor (damage), and flow regimes present. This analysis will act as a baseline measurement to determine the change in overall effectiveness and injectivity of the injection zone over time. A high-level procedure has been provided below. Note that a formal procedure will be provided to the US EPA prior to running the FOT.

1. Record static bottomhole pressure and temperature for a minimum of one hour.
2. Rig-up pump truck, ensure sufficient volume of fluid is present at location to begin testing.
3. Begin injection. Inject at constant rate for predetermined duration.
4. At the end of the injection period, shut the well in at the wing-valve(s). Record the time of shut-in, rate prior to shut-in, and the shut-in pressure.
5. Secure the well.
6. Rig-down pump truck.
7. After the pressure has been allowed to decline for approximately the same duration as the injection, the test can conclude.

The data from this test will be analyzed using pressure transient analysis software and the results will be included in the post-installation reporting. Gauge calibration records will also be provided at this time.

9. References

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: Aster Project.

Attachment 06: Testing and Monitoring, 2024, Underground Injection Control Class VI Permit Application: Aster Project.

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.