Longleaf CCS Hub

Longleaf CCS, LLC

Testing and Monitoring Plan and Reporting

40 CFR 146.90, 40 CFR 146.91

Facility Information

Facility Name: Longleaf CCS Hub

Facility Contact: Longleaf CCS, LLC

14302 FNB Parkway

Omaha, NE 68154

Well Locations: Mobile County, Alabama

LL#1: Latitude: 31.071303° N

Longitude: -88.094703° W

LL#2: Latitude: 31.070774° N

Longitude: -88.074523° W

LL#3: Latitude: 31.0447129° N

Longitude: -88.0736318° W

LL#4: Latitude: 31.0569516° N

Longitude: -88.1047433° W

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List of Acronyms/Abbreviations

AoR	Area of Review
CCS	Carbon capture and storage
CO_2	Carbon dioxide
CMG	Computer Modelling Group
DOE	Department of Energy
DAS	Distributed Acoustic Sensing
DTS	Distributed Temperature Sensing
EPA	Environmental Protection Agency
ERRP	Emergency and Remedial Response
ft	Feet
LL	Longleaf
mg/l	Milligrams per liter
MIT	Mechanical Integrity Test
MMcf/d	Million cubic feet/day
mol%	Percentage of total moles in a mixture made up by one constituent
msl	Mean sea level
mt	Metric tons
Mt	Millions of metric tons
mt/d	Metric tons per day
mt/y	Metric tons per day
MT/y	Millions of metric tons per year
PISC	Post-Injection Site Care
PNC	Pulsed Neutron Capture Log
ppmv	Parts per million volume
psi	Pounds per square inch, gauge
psia	Pounds per square inch, absolute
psi/ft	Pounds per square inch per foot
SS	Sub- Sea
TVD	True Vertical Depth
UIC	Underground Injection Control
USDW	Underground Source of Drinking Water

A. Overview of Testing and Monitoring Plan and Strategy

This Testing and Monitoring Plan is designed to ensure that injection and storage of CO_2 at the Longleaf CCS Hub is done safely, without endangerment to local USDWs or communities, and satisfies the requirements under 40 CFR 146.90.

Data collected during the implementation of this Plan will be used to confirm that injection procedures are operating as planned, that USDWs are protected, and that the CO_2 plume and pressure front are developing as predicted. The monitoring data will also be used to validate and update geologic and reservoir simulation models.

A key tenant of this Plan is deployment of well-based direct and indirect monitoring. Direct monitoring methods (pressure, flow rate, fluid sampling etc.) will be paired with indirect monitoring methods (fiber optic sensing, vertical seismic profiles, pulsed neutron capture logs, etc.) at a network of monitoring wells. This Plan is designed to incorporate monitoring using four injection wells (LL#1, LL#2, LL#3, and LL#4) and the series of monitoring wells constructed in the Longleaf CCS Hub storage area.

To protect USDWs and comply with 40 CFR 146.90, Longleaf CCS, LLC will construct a well-based testing and monitoring network that includes five types of wells. These five types of wells are listed below with their monitoring objective(s), their stratigraphic location, their approximate depth, and the number of each to be completed. **Figure 1** is a map of the Longleaf CCS Hub with the geographic locations of these monitoring wells. **Figure 2** is a stratigraphic column of the Longleaf CCS Hub site geology describing the stratigraphic location of each type of monitoring well.

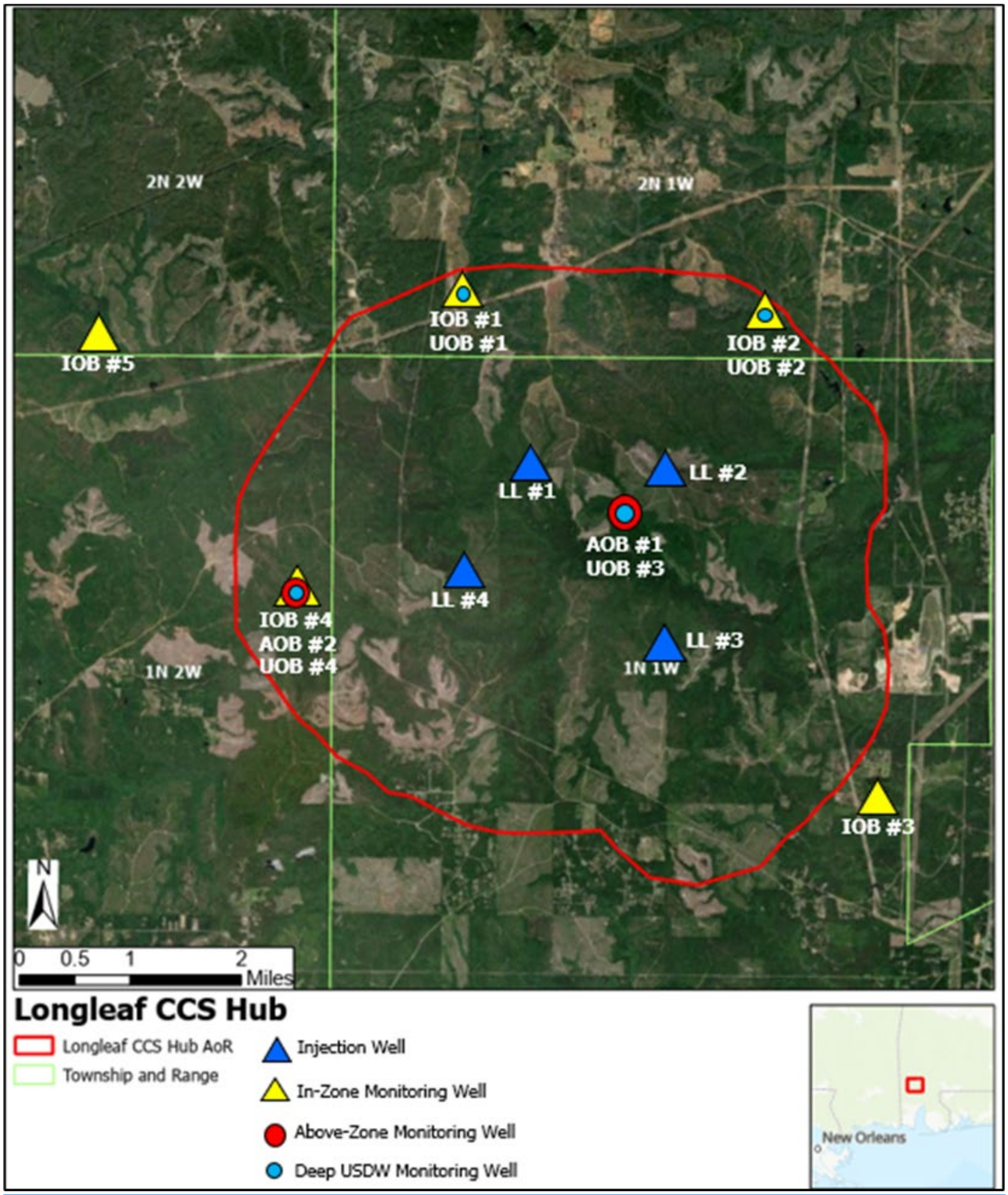

Figure 1: Locations of Proposed Injection and Monitoring Wells at the Longleaf CCS Hub.
Note: Shallow ground water monitoring wells are located on each well pad (10 total).

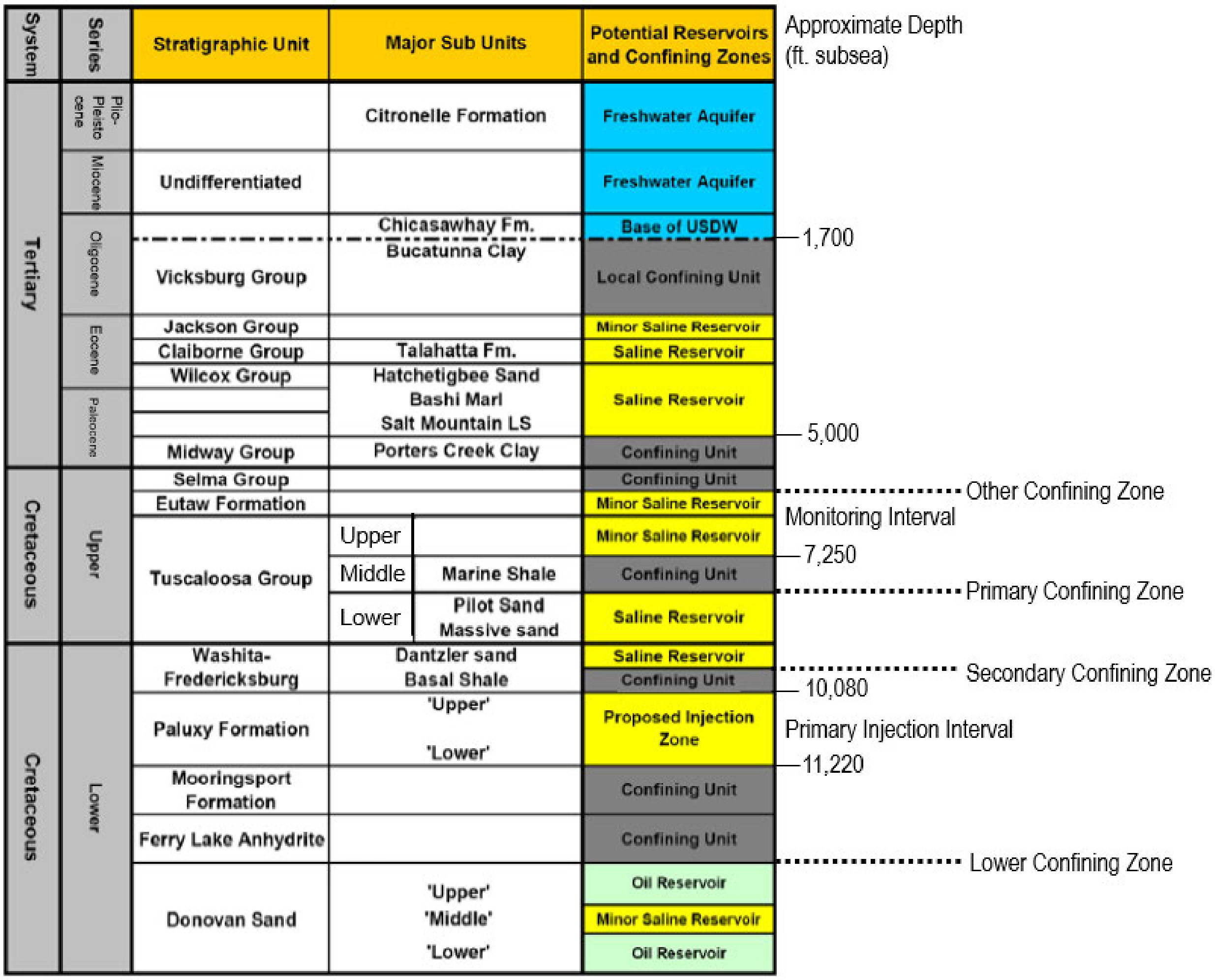

Figure 2: Geologic Stratigraphic Column at the Longleaf CCS Hub (modified from Pashin et al., 2008).[1]

Injection Wells

- Monitoring Objectives: Monitor CO_2 plume, pressure, injection process, and geophysical environment.
- Stratigraphic location: Paluxy Formation. Approximate depth of 10,100 ft MSL to top of Paluxy Formation.

[1] Pashin, J. C, McIntyre, M. R., Grace, R. L. B., Hills, D. J., "Southeastern Regional Carbon Sequestration Partnership (SECARB) Phase III, Final Report", Report to Advanced Resources International by Geological Survey of Alabama, Tuscaloosa, September 12, 2008

- Number to be completed: Four total injection wells for the Longleaf CCS Hub. See additional permits for other injection wells.

In-Zone Monitoring Wells

- Monitoring Objectives: Monitor CO_2 plume, pressure, and geophysical environment.
- Stratigraphic location: Paluxy Formation. Approximate depth of 10,100 ft MSL to top of Paluxy Formation.
- Number to be completed: Five total in-zone monitoring wells for the Longleaf CCS Hub. Located near the edges of expected plume migration in order to monitor the pressure front and track plume location and containment.

Above-Zone Monitoring Wells

- Monitoring Objectives: Monitor pressure, geochemistry, geophysical environment, and detect any leakage.
- Stratigraphic location: The Upper Tuscaloosa Formation. The first porous and permeable zone above the Tuscaloosa Marine Shale, the primary confining zone. Approximate depth of 7,200 ft SS.
- Number to be completed: Two total above-zone monitoring wells for the Longleaf CCS Hub. Located in areas where the increase in Paluxy formation pressure is expected to be the greatest.

Deep USDW Monitoring Wells

- Monitoring Objectives: Monitor geochemistry and detect any leakage.
- Stratigraphic location: The deepest USDW. The Chickasawhay Formation. Approximate depth of 1,700 ft SS.
- Number to be completed: Four total deep USDW monitoring wells for the Longleaf CCS Hub.

Shallow USDW Monitoring Wells

- Monitoring Objectives: Monitor geochemistry and detect any leakage.
- Stratigraphic location: Near-surface freshwater source.
- Number to be completed: Ten total shallow USDW monitoring wells for the Longleaf CCS. Located on existing well pads.

Monitoring data will be collected and used to ensure non-endangerment of USDWs and to confirm nominal injection operations. Additionally, this data will be used to validate and update rigorous numerical modeling performed during the planning and characterization phases of the project. The geologic model and reservoir simulation, being the primary method of forecasting the position, pressure, and saturation of the injected CO_2 within the project area, will ultimately support and demonstrate the safe and permanent storage of CO_2 throughout the project.

This Testing and Monitoring Plan will begin with field-wide monitoring protocols such as CO_2 stream analysis and corrosion monitoring. Then, the Plan will discuss the testing and monitoring activities at each of the five types of project wells, such as continuous monitoring, mechanical integrity testing, pressure falloff testing, plume and pressure front tracking, and groundwater and geochemistry monitoring. The Plan will also discuss further monitoring considerations such as seismicity and fault monitoring. Finally, the Plan will describe the proposed updating and reporting protocols.

B. Carbon Dioxide Stream Analysis

Longleaf CCS, LLC will analyze the CO_2 stream during the injection period to collect representative chemical and physical characteristic data, following the requirements of 40 CFR 146.90(a). Longleaf CCS, LLC expects multiple sources of CO_2 from the Mobile, AL region, with additional sources to be added throughout the life of the project. Each source will have a somewhat different gas stream composition based on the source's capture process, and the composition of the final injected gas stream will change depending on which sources are operational and not undergoing maintenance. As such, the CO_2 stream will be sampled continuously and represent the final gas, combined from all sources, that is injected. It is expected that the final CO_2 stream will have a mol% CO_2 concentration of at least 96%.

B.1. CO_2 Stream Sampling Location and Frequency

Longleaf CCS, LLC will analyze the CO_2 stream during the injection period to collect representative chemical and physical characteristic data. Baseline parameters will be established at the start of injection and occur continuously throughout the injection period using an on-site gas chromatograph. Longleaf CCS, LLC will report the results of the CO_2 stream analysis in semi-annual operational reports (see subsection *K.1. Semi-Annual Reporting* below).

In the event of unplanned disruptions to permitted injection activities that may affect the chemical and physical characteristics of the final CO_2 stream, Longleaf CCS, LLC will increase the frequency of CO_2 stream reporting to the UIC Program Director to confirm there are no significant changes and injection is continuing to operate as permitted.

B.2. CO_2 Stream Analytical Parameters

The CO_2 stream samples will be analyzed for the constituents shown in **Table 1** using a gas chromatograph. The list of parameters will be altered if analysis from the CO_2 stream demonstrates additional constituents to be considered. Amendments to this Plan must be approved by the UIC Program Director (see Section *J. Updating the Testing and Monitoring Plan* below).

B.3. CO_2 Stream Sampling Methods

CO_2 stream sampling will occur at the master meter located on the Injection Well LL#2 wellsite, the custody transfer point of the injection field. A gas chromatograph will be installed to analyze the CO_2 stream every 30 minutes to ensure the quality of the CO_2 stream. Physical samples will be sent quarterly to be analyzed for Hydrogen Sulfide and total Sulfur. Additional details regarding the specific procedures for CO_2 stream sample collection and precision are described in the *Quality Assurance and Surveillance Plan (QASP)*, which is attached to this Plan as an appendix.

Table 1: Summary of Anticipated CO_2 Stream Composition.

Component	Specification	Unit
Minimum CO_2	>96	mole%, dry basis
Water content	<20	lb/MMscf
Impurities (dry basis):		
Total Hydrocarbons	<2	mol%
Inert Gases (N_2, Ar, O_2)	<4	mol%
Hydrogen	<1	mol%
Alcohols, aldehydes, esters	<500	ppmv
Hydrogen Sulfide	<100	ppmv
Total Sulfur	<100	ppmv
Oxygen	<100	ppmv
Carbon monoxide	<100	ppmv
Glycol	<1	ppmv

B.4. Laboratory and Chain of Custody Procedures

All physical CO_2 stream samples collected quarterly will be analyzed by a third-party laboratory using standardized procedures for gas chromatography, mass spectrometry, detector tubes, and photo ionization. All sample containers will be labeled with a unique sample identification number and sampling date. Samples will be logged into a database with any notes. The sample chain of custody procedure is described in the *QASP*.

C. Corrosion Monitoring

Longleaf CCS, LLC will monitor for the corrosion of well materials that will be in contact with the CO_2 stream in order to confirm safe injection and storage of CO_2 and meet the requirements of 40 CFR 146.90(c). Well materials will be monitored for any evidence of cracking, pitting, or other signs of corrosion to ensure that components meet the minimum standards for material strength and performance.

C.1. Design and Materials

Coupons consisting of material that will directly contact the CO_2 stream will be placed within a flowline. Each sample will be attached to an individual holder and inserted in a flowthrough pipe arrangement, exposing the samples to the CO_2 stream and allowing access for removal and testing. The flowthrough pipe arrangement will be located downstream of all process compression, dehydration, and pumping equipment (i.e., at the beginning of the flowline to the well piping). A parallel stream of high-pressure CO_2 will be routed from the flowline through the corrosion monitoring system. This loop will operate while injection is occurring, providing representative exposure of the samples to the CO_2 composition, temperature, and pressures that will be seen at the wellhead and injection tubing. Injection will be able to continue while samples are removed for testing.

Coupon samples of the materials used to construct the CO_2 flowlines/pipelines, long string casing, injection tubing, wellhead, and packers will be monitored for corrosion. The construction materials for these pieces of equipment are listed below in **Table 2** and are consistent with the materials listed in Section *4.1 Well Design* of the *Application Narrative*.

Table 2: List of Equipment Coupon with Material of Construction.

Equipment Coupon	Material of Construction
Pipeline	API 5L X42 PSL2, API 5L X52 PSL2 API 5L X60, API 5L X65 PSL2 API 5L or X70 PSL2 carbon steel
Long String Casing (Depths 8,000 ft – 11,400 ft)	13% Chromium Stainless Steel
Injection Tubing	13% Chromium Stainless Steel
Wellhead	13% Chromium Stainless Steel
Packers	13% Chromium Stainless Steel

C.2. Methodology, Frequency, and Handling

Corrosion monitoring coupons will be weighed, measured, and photographed prior to initial exposure. Then, coupons will be removed quarterly and assessed for corrosion using the NACE RP0775-2018[2] standard or a similarly accepted standard practice for preparing, cleaning, and evaluating corrosion test specimens. Upon removal, coupons will be photographed and inspected visually with a minimum of 10x power for evidence of

[2] The National Association of Corrosion Engineers (NACE) Standard RP0775, (2018). *Preparation, Installation, Analysis, And Interpretation of Corrosion Coupons In Oilfield Operations*, Houston, TX. ISBN 1-57590-086-6.

corrosion such as cracking or pitting. The weight and size (thickness, width, and length) of the coupons will be measured and recorded to within 0.0001 gm and 0.0001 inch. The corrosion rate will be calculated as the weight loss during the exposure period divided by the duration of exposure (i.e., weight loss method).

Longleaf CCS, LLC will also employ additional monitoring techniques to ensure USDW protection and guard against corrosion. These techniques include cased hole pulsed neutron capture (PNC) logs, ultrasonic cement bond logs as necessary, mechanical integrity testing (MIT), and annular pressure monitoring. The location and frequency of these techniques are described in *Section D. Injection Well Monitoring, Section E. In-Zone Observation Well Monitoring, and Section F. Above-Zone Observation Well Monitoring.*

Casing and tubing will be evaluated for corrosion as necessary by running wireline casing inspection logs. Furthermore, wireline tools can be lowered into the well to directly measure properties of the well tubulars that indicate corrosion. These tools, which may be used to monitor and assess the condition of well tubing and casing, include:

- Mechanical casing evaluation tools, referred to as calipers, have multiple articulated arms attached to the tool that measure the inner diameter of the tubular as the caliper is raised or lowered through the well.
- Ultrasonic tools, which are capable of measuring wall thickness in addition to the inner diameter of the well tubular and can also provide information about the outer surface of the casing or tubing.
- Electromagnetic tools, which are capable of distinguishing between internal and external corrosion effects using variances in the magnetic flux of the tubular being investigated. These tools are able to provide circumferential images with high resolution such that pitting depths, due to corrosion, can often be accurately measured.

D. Injection Well Monitoring

D.1. Summary of Injection Well Monitoring Activities

Injection wells at the Longleaf CCS Hub will be completed in the Paluxy Formation at an approximate depth of 10,100 ft MSL. All four injection wells will provide key pressure data, plume tracking, and geophysical monitoring data that will confirm the safe injection and storage of CO_2 without endangerment to USDWs. Testing and monitoring activities will include the continuous monitoring of injection parameters, mechanical integrity testing, pressure transient testing, and plume and pressure front tracking. **Table 3** below displays the testing and monitoring activities that will be deployed at the four Longleaf CCS Hub injection wells. **Figure 1** shows the location of Injection Wells LL#1, LL#2, LL#3, and LL#4 the Longleaf CCS Hub.

Table 3: Summary of Testing and Monitoring Activities to be Conducted at the Injection Wells.

Monitoring Activity/Test		Purpose	Baseline Frequency	Injection Period Frequency	Post-Injection Site Care Frequency
Fiber Optic / Seismic Monitoring	Distributed Acoustic Sensing (DAS)	Indirect geophysical monitoring	Beginning before injection	Continuous	Continuous
	Distributed Temperature Sensing (DTS)	Well integrity/leak detection	Beginning before injection	Continuous	Continuous
Pulsed Neutron Capture Log (PNC)		Geophysical monitoring	Once before injection	3yrs after injection begins; Every 5yrs after	At end of injection; Every 5yrs after
Mechanical Integrity Tests		Well integrity/leak detection	Once before injection	Annually	Annually
Pressure Transient Test		Geophysical monitoring	Once before injection	3yrs after injection begins; Every 5yrs after	At end of injection; Every 5yrs after
Bottomhole Pressure Monitoring		Pressure monitoring	Beginning before injection	Continuous surface read-out	Continuous surface read-out
Wellhead Pressure Monitoring	Tubing	Pressure monitoring/ leak detection	Beginning before injection	Continuous	Continuous
	Annulus	Pressure monitoring/ leak detection	Beginning before injection	Continuous	Continuous
Injection Rate and Volume Monitoring		Injection process monitoring	N/A	Continuous	N/A

D.2. Injection Well Continuous Monitoring

Pursuant to 40 CFR 146.90(b), Longleaf CCS, LLC will install and use continuous recording devices to monitor the injection pressure, rate, and volume; the pressure of the annulus between the tubing and the long string casing; the annulus fluid volume added; and the temperature of the CO_2 stream. All monitoring will be continuous for the duration of the injection period. Parameters, device, location, and sampling frequency are outlined in **Table 4** below.

Above-ground pressure and temperature instruments shall be calibrated over the full operational range annually, using American National Standards Institute (ANSI) or other industry recognized standards. Pressure transducers shall have a drift stability of less than 3 psi over the operational period of the instrument and an accuracy of ± 5 psi. Sampling rates will be at least once every 5 seconds. Temperature sensors will be accurate to within one degree Celsius. Downhole and surface pressure and temperature gauge specifications are described in more detail in the *QASP.*

Injection rate (flow) will be monitored with a Coriolis mass flowmeter at the wellhead. The flowmeter will be calibrated for the entire expected range of flow rates using generally accepted standards and accurate to within ± 1.0 percent.

D.2.1. Injection Rate and Pressure Monitoring

Longleaf CCS, LLC will monitor injection operations using a distributive process control system (DPCS). The Surface Facility Equipment & Control System will limit maximum instantaneous flow to 4,110 mt/d and/or limit the well head pressure to 2,000 psia, which corresponds to well below the regulatory requirement to not exceed 90% of the injection zone's fracture pressure. Maximum annual injection will not exceed 1.25 Mt/y or an average of 3,425 mt/d. All critical system parameters (e.g., pressure, temperature, and flow rate) will have continuous electronic monitoring with signals transmitted back to a master control system. The system will sound an alarm and shutdown operations should specified control parameters exceed their normal operating range at any time. Longleaf CCS, LLC supervisors and operations personnel will have the capability to monitor the status of the system comprehensively from distributive control centers.

Table 4: Sampling Devices, Locations, and Frequencies for Continuous Monitoring at Injection Wells.

Parameter	Device(s)	Location	Min. Sampling Frequency (active / shut-in)	Min. Recording Frequency (active / shut-in)
Injection Pressure Monitoring	Bottomhole surface read-out pressure gauge	Downhole	5 sec. / 4 hours	5 mins. / 4 hours
Injection Rate Monitoring	Coriolis flow meter and flow computer	Surface	5 sec. / 4 hours	5 mins. / 4 hours
Injection Volume Monitoring	Coriolis flow meter	Surface	5 sec. / 4 hours	5 mins. / 4 hours
Casing Pressure Monitoring	Continuous annular pressure gauge, annulus fluid reservoir, pressure regulators, tank fluid indication	Surface	5 sec. / 4 hours	5 mins. / 4 hours
Tubing Pressure Monitoring	Continuous surface pressure gauge	Surface	5 sec. / 4 hours	5 mins. / 4 hours
Annulus Fluid Volume Monitoring	Continuous surface pressure gauge	Surface	5 sec. / 4 hours	5 mins. / 4 hours
CO_2 Stream Temperature Monitoring	Surface temperature gauge	Surface	5 sec. / 4 hours	5 mins. / 4 hours
Distributed Acoustic Sensing (DAS)	Fiber optic cable	Downhole	<1 sec. / <1 sec.	<5 min / <10 min
Distributed Temperature Sensing (DTS)	Fiber optic cable	Downhole	10 min / 10 min	10 min / 10 min

Notes:

- 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 is 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.

D.2.2. Injection Well Annulus Pressure Monitoring

Longleaf CCS, LLC will use the procedures below to monitor annular pressure. The following procedures will be used to minimize the potential for any unpermitted fluid movement into or out of the annulus:

- The annulus between the tubing and the long string of casing will be filled with brine and a corrosion inhibitor (*3.1 Operational Conditions* in the *Injection Well Operations Plan)*.
- The surface annulus pressure will be kept within a range of 375 psia ± 125 psia.
- At all times during injection, the bottomhole tubing – long-string casing annulus pressure will be maintained at a pressure higher than the bottomhole injection pressure of the injection interval.

Figure 3 below shows the process instrument diagram for the injection well annulus protection system. The annular monitoring system consists of a continuous annular pressure gauge, a pressurized annulus fluid reservoir (annulus head tank), pressure regulators, and tank fluid level indicator. The annulus system will maintain annulus pressure by controlling the pressure on the annulus head tank using either compressed nitrogen, CO_2, or pressure pump.

The annular pressure between the tubing and the long-string casing will be maintained at a higher pressure than the injection pressure, at bottomhole conditions, during injection and will be monitored by the Longleaf CCS, LLC control system gauges. The annulus head tank pressure will be controlled by pressure regulators or pumps; one set of regulators or pumps will be used to maintain pressure above injection pressure if needed by adding compressed nitrogen or CO_2 and the other to relieve pressure if needed by venting gas or fluid from the annulus head tank. Any changes to the composition of annular fluid will be submitted to the UIC Program Director for approval.

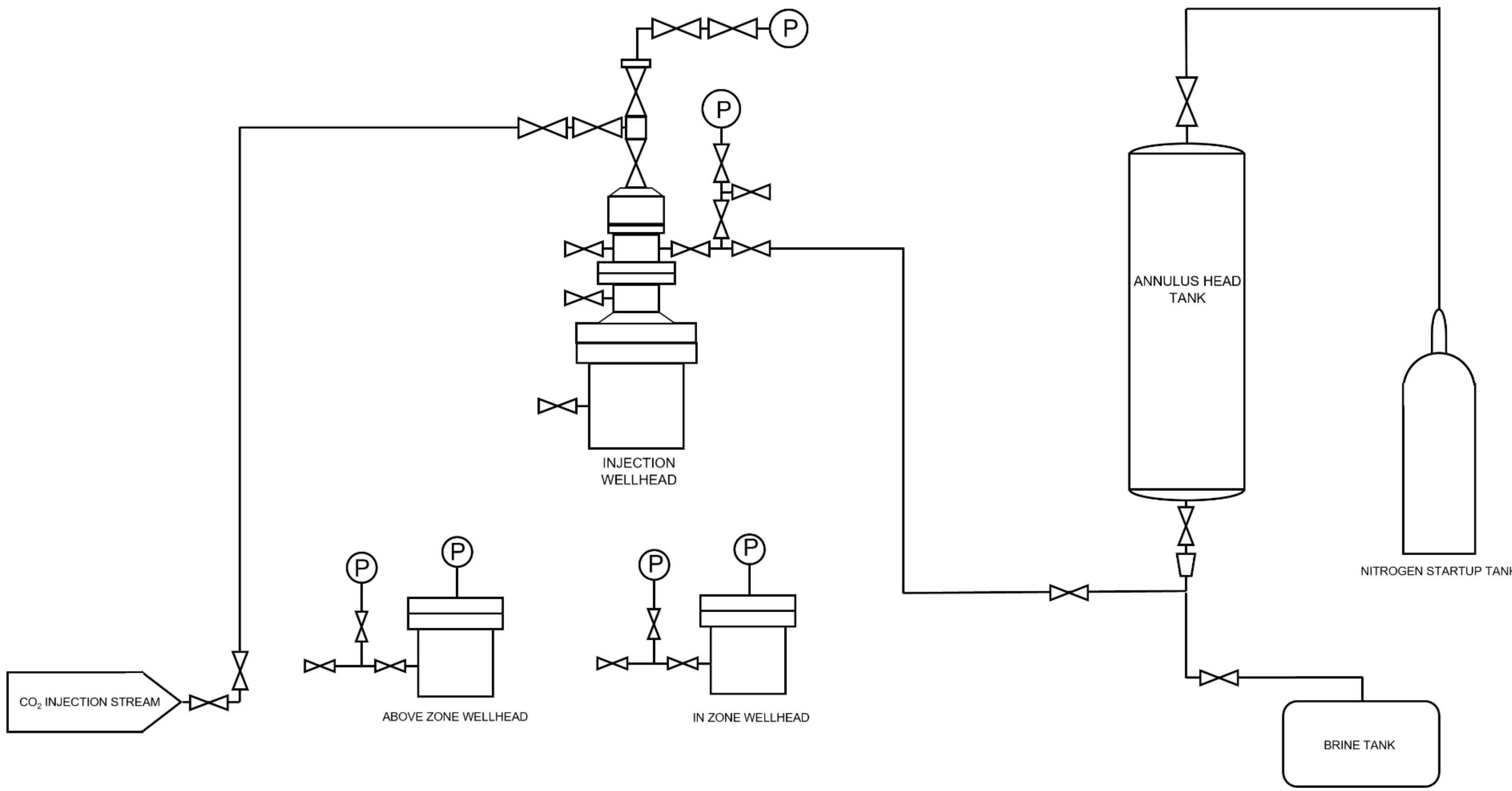

Figure 3: Annular Monitoring System General Layout

If system communication were to be lost for greater than 60 minutes, project personnel will observe and monitor manual gauges in the field every eight hours or once per shift for both wellhead surface pressure and annulus pressure, while also recording hard copies of the data until communication is restored.

Average annular pressure, annulus tank fluid level, and volume of fluid added or removed from the system will be recorded daily and reported as monthly averages in the semi-annual report (see subsection *K.1 Semi-Annual Reporting*).

As detailed in the *Emergency and Remedial Response Plan (ERRP)*, significant changes in the casing-tubing annular pressure attributed to well mechanical integrity will be investigated.

D.2.3. Fiber Optic Cable Deployment

Longleaf CCS, LLC will deploy fiber optic cable on the outside of the long string casing for all injection wells, equipped through the Tuscaloosa Marine Shale. Fiber optic cable will enable continuous micro-seismic and geophysical monitoring through distributed acoustic sensing (DAS) and well integrity assurance and leak detection through distributed temperature sensing (DTS).

D.3. Injection Well Mechanical Integrity Testing

Longleaf CCS, LLC will conduct at least one of the tests presented below in **Table 5** periodically during the injection phase to verify external mechanical integrity as required by 40 CFR 146.90(e). Demonstrating and maintaining the mechanical integrity of the injection well is key to protecting USDWs because the well is a possible conduit for fluid movement through the confining interval.

The condition of the cement and casing will be verified using downhole logging techniques and tools to determine there is no fluid flow behind the casing or channels in the cement. An ultrasonic cement bond inspection log and an electromagnetic casing inspection log will be run through the entire length of the long-string casing before injection begins. During injection, the absence of any leaks in the casing, injection tubing, and packer will be demonstrated using annulus pressure tests conducted annually.

Table 5. Showing MIT Description and Frequency at Injection Wells.

Test Description	Frequency During Injection Period
Pressure Falloff Testing	Minimum of once per 5 years, during planned well maintenance
Annulus Pressure Test	Annually
Annulus Pressure Monitoring	Continuous
Pulsed Neutron Capture (PNC) Log	Baseline before injection; 3yrs after injection begins; Every 5yrs thereafter
Distributed Temperature Sensing (DTS)	Continuous
Temperature Logging	Baseline before injection; 3yrs after injection begins; Every 5yrs thereafter
Ultrasonic Cement Bond Inspection Log	Once before injection
Electromagnetic Casing Inspection Log	Once before injection

PNC logs will be run at least once prior to the start of CO_2 injection, 3 years after injection begins, and every five years thereafter until the well is plugged and abandoned. PNC logs can identify potential fugitive CO_2 movement by quantifying the fluid saturations around the wellbore and the presence of CO_2[3]. Following a baseline, subsequent logs can be compared to determine changes in fluid flow and saturation adjacent to the wellbore and detect any formation of channels or other fluid isolation concerns related to the well. A temperature log will be deployed in conjunction with PNC logging to further evaluate mechanical integrity.

Continuous DTS monitoring will provide additional comprehensive mechanical integrity confirmation by continuously monitoring for areas along the wellbore with anomalous changes in temperature.

[3] Conner, A., Place, M., Chace, D., and Gupta, N., September 2020, "Pulsed Neutron Capture for Monitoring CO_2 Storage with Enhanced Oil Recovery in Northern Michigan", Battelle, Volume II.F, Midwestern Regional Carbon Sequestration Partnership (MRCSP) Phase III, Submitted to The U.S. Department of Energy, National Energy Technology Laboratory, DOE MRCSP Project #DE-FC26-05NT42589, https://www.osti.gov/servlets/purl/1773351.

Notice of intent to conduct routine pressure tests, temperature logs, and any additional mechanical tests, logs, or inspections will be provided to the UIC Program Director at least 30 days prior to the demonstration of mechanical integrity. In the case of unscheduled or remedial well activity, the UIC Program Director will receive a remediation plan that includes a MIT activity to demonstrate well integrity following the intervention (see *ERRP*). The results of any injection well test or MIT will be provided to the UIC Program director within 30 days after the test.

D.4. Injection Well Pressure Transient Testing

Pursuant to 40 CFR 146.90(f), Longleaf CCS, LLC will perform pressure falloff tests during the injection phase to confirm site characterization information, inform AoR reevaluation, and verify that the project is operating properly and the injection zone is responding as predicted. Tests will occur once before injection (baseline), after 3 years from the start of injection, and every 5 years thereafter until well abandonment.

A pressure falloff test includes a period of injection followed by a period of non-injection or shut down. Normal injection using the CO_2 stream provided by the Longleaf CCS Hub will be used during the injection period preceding the shut-in portion of the falloff tests. Injection rates on a well-by-well basis are continuously recorded and will be employed in the analysis of the continuously recorded subsurface pressure data. The Operator will strive to have a minimum of one week of relatively continuous injection to precede the shut-in portion of the falloff test. This data will be measured using a surface readout downhole gauge.

Because surface readout will be used and downhole recording memory restrictions will be eliminated, data will be collected at intervals of five seconds or less for the duration of test. The shut-in period of the falloff test will be a minimum of four days, continuing until adequate pressure transient data are collected to calculate the average pressure. A report containing the pressure falloff data and interpretation of the reservoir ambient pressure will be submitted to the UIC Program Director within 90 days of the test. Pressure sensors used for this test will be the wellhead sensors and a downhole gauge for the pressure falloff test. Each gauge will be of a type that meets or exceeds ASME B 40.1[4] Class 2A (0.5% accuracy across full range of pressures). Wellhead and downhole gauge specifications are described in detail in the *QASP.*

D.5. Injection Well Plume and Pressure Front Tracking

Longleaf CCS, LLC will utilize direct and indirect methods to track the extent of the CO_2 plume and the presence or absence of elevated pressure to meet the requirements of 40 CFR 146.90(g).

Direct monitoring of pressure will be used to assess the lateral extent of injected CO_2 and the pressure front within the injection zone. In addition to surface methods, downhole geophysical methods and logging tools will be used to provide an indirect measure of CO_2 plume development and spatial distribution. This section describes the proposed injection zone monitoring program.

During the active injection phase, continuous (i.e., uninterrupted) downhole monitoring of pressure will be conducted in the four CO_2 injection wells. The pressure gauges will be removed from the wells only when they require maintenance or when necessitated by other activities (e.g., well maintenance). Formation fluid sampling will not occur in the four CO_2 injection wells during the operational phase so as not to interfere with injection operations.

The primary objective of monitoring injection zone pressure is to provide data needed to adequately assess the lateral extent of injected CO_2 and the pressure front over time. Specific objectives for monitoring injection zone pressure include the following:

- Calibrate the numerical models that will be used to help track CO_2 and pressure in the injection zone.
- Guard against over-pressuring, which could induce unwanted fracturing of the injection zone or the overlying confining zone(s).

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[4] The American Society of Mechanical Engineers (ASME), B40.100 – 2022, “Pressure Gauges and Gauge Attachments”, Published 2022, ISBN 9780791875285.

- Determine the need for well rehabilitation.
- Assess injection zone properties (e.g., permeability, porosity, reservoir size) within progressively larger areas of the reservoir as the pressure front advances.

D.5.1. Plume Monitoring

Longleaf CCS, LLC will collect baseline, pressurized fluid samples from the injection interval (Paluxy Formation) at each of the four injection wells in accordance with 40 CFR 146.87(b)-(c). More information on the parameters to be analyzed as part of fluid sampling in the injection zone as well as the results from injection zone fluid sampling are provided in the ***Pre-Operational Testing Plan***. Longleaf CCS, LLC will not collect fluid samples from the injection wells during the injection period to avoid interrupting normal injection operation.

Indirect plume monitoring will be conducted using PNC logs and vertical seismic profiles (VSPs) to monitor CO_2 saturations and to track the movement of the expected CO_2 plume. Longleaf CCS, LLC will conduct PNC logging and VSPs once before injection, 3 years after injection begins, and every 5 years thereafter during the injection period, as well as before the plugging and abandonment of any injection well.

Longleaf CCS, LLC will also employ a temperature log that will be deployed and collected in conjunction with each PNC logging run. The information from these logging activities will provide ample data sets to calibrate the geologic models incorporated within the numerical models to the field performance data.

D.5.2. Pressure-front Monitoring

Injection of CO_2 into a saline aquifer generates pressure perturbations that diffuse through the fluid-filled pores of the geologic system. The objective of pressure monitoring is to record the pressure signal at the source (i.e., injection well) and one or more monitoring wells to infer important rock and fluid characteristics such as permeability and total compressibility from the analysis of the pressure data. Pressure monitoring information also provides input for the calibration of numerical models, where injection zone properties are adjusted to match the observed pressure data with corresponding simulation predictions. This provides confirmation of predictions regarding the extent of the CO_2 plume, pressure buildup, and the occurrence of fluid displacement into overlying formations.

Pressure in the injection zone will be monitored continuously with a downhole surface read-out gauge at all four injection wells. Pressure monitoring as a component of the overall MVA program provides multiple benefits. Inferences about formation permeability at scales comparable to that of CO_2 plume migration can be made (as opposed to that from small centimeter-scale core samples). Permeability values estimated for different regions of the injection zone may indicate the presence of anisotropy and, hence, suggest potential asymmetry in the plume trajectory. Such information can be useful in adapting the monitoring strategy.

Pressure monitoring in the injection well will be performed using a real-time monitoring system with surface read-out capabilities so that pressure gauges do not have to be removed from the well to retrieve data. The following measures will be taken to ensure that the pressure gauges are providing accurate information on an ongoing basis:

- High-quality (high-accuracy, high-resolution) gauges with low drift characteristics will be used.
- Gauge components (gauge, cable head, cable) will be manufactured of materials designed to provide a long-life expectancy for the anticipated downhole conditions.
- Upon acquisition, a calibration certificate will be obtained for every pressure gauge. The calibration certificate will provide the manufacturer's specifications for range, accuracy (% full scale), resolution (% full scale), drift (< psi per year) and calibration results for each parameter. The calibration certificate will also provide the date that the gauge was calibrated, and the methods and standards used.
- Gauges will be installed above the completion packer in the long-string casing-tubing annulus so they can be removed if necessary for recalibration by removing the tubing string. Redundant gauges may be run on the same cable to provide confirmation of downhole pressure and temperature.

- Upon installation, all gauges will be tested to verify they are functioning (reading/transmitting) correctly.
- Gauges will be pulled and recalibrated each time a workover occurs that involves removal of tubing. A new calibration certificate will be obtained each time a gauge is re-calibrated.

E. In-Zone Observation Well Monitoring

E.1. Summary of In-Zone Monitoring Activities

In-zone monitoring wells at the Longleaf CCS Hub will be completed in the Paluxy Formation at an approximate depth of 10,100 ft SS. Five in-zone monitoring wells will provide key data on pressure, plume tracking, and geophysical monitoring that will confirm the safe injection and storage of CO_2 without endangerment to USDWs. Testing and monitoring activities will include continuous pressure monitoring, mechanical integrity testing, pressure transient testing, and plume and pressure front tracking. **Table 6** below displays all of the testing and monitoring activities that will be deployed at each of the five in-zone monitoring wells.

E.2. Placement of In-Zone Observation Wells

The primary objective of the five in-zone monitoring wells at the Longleaf CCS Hub is to directly monitor the movement and development of the CO_2 plume and pressure front. The spatial distribution of in-zone monitoring wells, shown in **Figure 1**, will allow Longleaf CCS, LLC to track and confirm the CO_2 plume over the course of the 30-year injection period.

Table 6: Summary of Testing and Monitoring Activities at In-Zone Monitoring Wells.

Monitoring Activity/Test		Purpose	Baseline Frequency	Injection Period Frequency	Post-Injection Site Care Frequency
Fiber Optic / Seismic Monitoring	Distributed Acoustic Sensing (DAS)	Indirect geophysical monitoring	Beginning before injection	Continuous	Continuous
	Distributed Temperature Sensing (DTS	Well integrity/leak detection	Beginning before injection	Continuous	Continuous
Pulsed Neutron Capture Log (PNC)		Geophysical monitoring	Once before injection	3yrs after injection begins; Every 5yrs after	At end of injection; Every 5yrs after
Mechanical Integrity Tests		Well integrity/leak detection	Once before injection	Annually	Annually
Bottomhole Pressure Monitoring		Pressure monitoring	Beginning before injection	Continuous surface read-out	Continuous surface read-out
Wellhead Tubing and Annulus Pressure Monitoring		Pressure monitoring/leak detection	Beginning before injection	Continuous	Continuous

Longleaf CCS, LLC chose the locations for the in-zone monitoring wells based on the expected pressure front and the CO_2 plume development as determined through a rigorous modeling approach, the details of which are provided in section *A.3.d Executing the Computational Model Section* of the *Area of Review and Corrective Action Plan*. Near-field in-zone monitoring wells allow the development of the pressure front and CO_2 plume to be monitored while far-field in-zone monitoring wells ensure lateral containment. These in-zone monitoring wells provide Longleaf CCS, LLC with pressure data to validate the geologic and computational models to confirm that the CO_2 plume is behaving in an expected and predictable manner.

E.3. In-Zone Observation Well Continuous Monitoring

Longleaf CCS, LLC will install and use continuous recording devices to monitor the formation pressure and the pressure of the annulus between the tubing and the long string casing. All monitoring will be continuous for the duration of the injection period. Parameters, device, location, and sampling frequency are outlined in **Table 7** below.

Table 7: Sampling Devices, Locations, and Frequencies for Continuous Monitoring at In-Zone Monitoring Wells.

Parameter	Device(s)	Location	Min. Sampling Frequency (active / shut-in)	Min. Recording Frequency (active / shut-in)
Injection Interval Pressure Monitoring	Bottomhole surface read-out pressure gauge	Downhole	5 sec. / 4 hours	5 mins. / 4 hours
Casing Pressure Monitoring	Continuous annular pressure gauge	Surface	5 sec. / 4 hours	5 mins. / 4 hours
Tubing Pressure Monitoring	Continuous surface pressure gauge	Surface	5 sec. / 4 hours	5 mins. / 4 hours
Distributed Acoustic Sensing (DAS)	Fiber optic cable	Downhole	<1 sec. / <1 sec.	<5 min / <10 min
Distributed Temperature Sensing (DTS)	Fiber optic cable	Downhole	10 min / 10 min	10 min / 10 min

Notes:

- 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 is 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.

Above-ground pressure instruments shall be calibrated over the full operational range at least annually using ANSI or other industry recognized standards. Pressure transducers shall have a drift stability of less than 3 psi over the operational period of the instrument and an accuracy of ± 5 psi. Sampling rates will be at least once every 5 seconds.

Longleaf CCS, LLC will deploy fiber optic cable on the outside of the long string casing for all in-zone monitoring wells through the Tuscaloosa Marine Shale. Fiber optic cable will enable continuous micro-seismic and geophysical monitoring through DAS and well integrity assurance and leak detection through DTS.

E.4. In-Zone Observation Well Mechanical Integrity Testing

Longleaf CCS, LLC will conduct at least one of the tests presented below in **Table 8** periodically during the injection phase to verify external mechanical integrity in all in-zone monitoring wells. Demonstrating and maintaining the mechanical integrity of the in-zone monitoring wells is key to protecting USDWs because these wells are a possible conduit for fluid movement through the confining interval and will also satisfy the State Oil and Gas Board of Alabama regulatory guidelines for monitoring wells.

Table 8. Showing MIT Test Description and Frequency at In-Zone Monitoring Wells.

Test Description	Frequency During Injection Phase
Annulus Pressure Test	Annually
Annulus Pressure Monitoring	Continuous
Pulsed Neutron Capture (PNC) Log	Baseline before injection; 3yrs after injection begins; Every 5yrs thereafter
Distributed Temperature Sensing (DTS)	Continuous
Temperature Logging	Baseline before injection; 3yrs after injection begins; Every 5yrs thereafter
Ultrasonic Cement Bond Inspection Log	Once before injection

The condition of the cement and casing will be verified using downhole logging techniques and tools to determine there is no fluid flow behind the casing or channels in the cement. An ultrasonic cement bond inspection log and electromagnetic casing inspection log will be run through the entire length of the long-string casing during well construction.

PNC logs will be run at least once prior to the start of CO_2 injection, 3 years after injection begins, and every five years thereafter until the well is plugged and abandoned. PNC logs can identify potential fugitive CO_2 movement by quantifying the flow of water around the wellbore and the presence of CO_2. Following a baseline, subsequent logs can be compared to determine changes in fluid flow and saturation adjacent to the wellbore and detect any formation of channels or other fluid isolation concerns related to the well. A temperature log will be deployed in conjunction with PNC logging to further evaluate mechanical integrity.

Continuous DTS monitoring will provide additional comprehensive mechanical integrity confirmation by continuously monitoring for areas along the wellbore with anomalous changes in temperature. The annulus between the tubing and the long string of casing will be filled with brine and a corrosion inhibitor and a pressure gauge will continuously monitor the annular pressure.

E.5. In-Zone Plume and Pressure Front Tracking

Longleaf CCS, LLC will utilize 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).

Direct monitoring of pressure will be used to assess the lateral extent of injected CO_2 and the pressure front within the injection zone. In addition to surface methods, downhole geophysical methods and logging tools will be used to provide an indirect measure of CO_2 plume development and spatial distribution. This section describes the proposed injection zone monitoring program for the five in-zone monitoring wells.

E.5.1. Plume Monitoring

As discussed in subsection *E.2* above, the locations of the five in-zone monitoring wells will enable Longleaf CCS, LLC to directly monitor the movement and progression of the CO_2 plume. The spatial distribution of the monitoring well network will allow Longleaf CCS, LLC to validate and update its reservoir model with real pressure and saturation data and confirm that the CO_2 plume is behaving as expected.

Indirect plume monitoring will be conducted using PNC logs and VSPs to monitor CO_2 saturations and to track the movement of the expected CO_2 plume. Longleaf CCS, LLC will conduct PNC logging and VSPs once before injection, 3 years after injection begins, and every 5 years thereafter during the injection phase, as well as before the plugging and abandonment of any injection well.

Longleaf CCS, LLC will also employ a temperature log that will be deployed and collected in conjunction with each PNC logging run. The information from these logging activities will provide data to calibrate the geologic and computational models to the field performance data.

E.5.2. Pressure-front monitoring details

Pressure monitoring at the five in-zone monitoring wells will be performed using a real-time monitoring system with surface read-out capabilities so that pressure gauges do not have to be removed from the well to retrieve data. The measurements listed in section *D.5.2 Injection Wells Pressure Monitoring* will be taken to ensure that the pressure gauges provide accurate information on an ongoing basis.

The pressure data collected will be used to track the pressure front over the operational period and provide valuable feedback to the computational reservoir model. An abundance of pressure data from the injection interval will aid Longleaf CCS, LLC during AoR reevaluations to ensure the most accurate geologic and reservoir model is being used.

F. Above-Zone Observation Well Monitoring

F.1. Summary of Above-Zone Well Monitoring Activities

Deep USDW monitoring wells at the Longleaf CCS Hub will be completed in the first porous and permeable interval above the confining unit, the Tuscaloosa Marine Shale in the Upper Tuscaloosa Formation at an approximate depth of 7,200 ft SS. Two above-zone monitoring wells will be completed to monitor pressure, geochemistry, and the geophysical environment and to detect any CO_2 leakage. Testing and monitoring activities will include the continuous monitoring of pressures, mechanical integrity testing, pressure transient testing, geophysical monitoring/plume and pressure front tracking, and ground water and geochemistry testing. **Table 9** below displays the testing and monitoring activities that will be deployed at the Longleaf CCS Hub above-zone monitoring wells.

F.2. Placement of Above-Zone Observation Wells

Longleaf CCS, LLC considered geologic site data, the presence of artificial penetrations, community impact, and the results of an extensive reservoir modeling effort to determine the location for above-zone monitoring wells that will best ensure non-endangerment to USDWs and local communities. The placement of the two above-zone monitoring wells is based on an internally conducted risk assessment. **Figure 1** provides the location of the one near-field above-zone monitoring well and the one far-field above-zone monitoring well.

Table 9: Summary of Testing and Monitoring Activities at Above-Zone Monitoring Wells.

Monitoring Activity/Test		Purpose	Baseline Frequency	Injection Period Frequency	Post-Injection Site Care Frequency
Fiber Optic / Seismic Monitoring	Distributed Acoustic Sensing (DAS)	Indirect geophysical monitoring	Beginning before injection	Continuous	Continuous
	Distributed Temperature Sensing (DTS	Well integrity/leak detection	Beginning before injection	Continuous	Continuous
Pulsed Neutron Capture Log (PNC)		Geophysical monitoring	Once before injection	3yrs after injection begins; Every 5yrs after	At end of injection; Every 5yrs after
Mechanical Integrity Tests		Well integrity/leak detection	Once before injection	Every 5yrs	Every 5yrs
Bottomhole Pressure Monitoring		Pressure monitoring	Beginning before injection	Continuous surface read-out	Continuous surface read-out
Wellhead Tubing and Annulus Pressure Monitoring		Pressure monitoring/leak detection	Beginning before injection	Continuous	Continuous
Fluid Sampling		Leak detection/ geochemistry monitoring	At least 3 sampling events prior to injection	Quarterly for first yr; Annually thereafter	Annually

Above-zone monitoring well AOB#1 will be placed in the middle of the four planned injection wells at the Longleaf CCS Hub. The results of reservoir modeling have determined that this is where pressure will increase the greatest in the Paluxy Formation injection interval during the injection period. Above-zone monitoring well AOB#2 will be placed in the far-field towards the western edge of the AoR to provide information as the CO_2 plume migrates up-structure.

Existing well penetrations are not expected to be a risk for CO_2 leakage at the Longleaf CCS Hub. There are no existing wells that penetrate the Tuscaloosa Marine Shale within the AoR.

F.3. Above-Zone Observation Well Continuous Monitoring

Longleaf CCS, LLC will install and use continuous recording devices to monitor the above-zone formation pressure and the pressure of the tubing at the wellhead, and the pressure of the annulus between the tubing and the long string casing. All monitoring will be continuous for the duration of the injection period. Parameters, device, location, and sampling frequency are outlined in **Table 10** below.

Table 10: Sampling Devices, Locations, and Frequencies for Continuous Monitoring at Above-Zone Monitoring Wells.

Parameter	Device(s)	Location	Min. Sampling Frequency (active / shut-in)	Min. Recording Frequency (active / shut-in)
Above-Zone Interval Pressure Monitoring	Bottomhole surface read-out pressure gauge	Downhole	5 sec. / 4 hours	5 mins. / 4 hours
Casing Pressure Monitoring	Continuous annular pressure gauge	Surface	5 sec. / 4 hours	5 mins. / 4 hours
Tubing Pressure Monitoring	Continuous surface pressure gauge	Surface	5 sec. / 4 hours	5 mins. / 4 hours
Distributed Acoustic Sensing (DAS)	Fiber optic cable	Downhole	<1 sec. / <1 sec.	<5 min / <10 min
Distributed Temperature Sensing (DTS)	Fiber optic cable	Downhole	10 min / 10 min	10 min / 10 min

Notes:

- 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 is 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.

Above-ground pressure instruments shall be calibrated over the full operational range at least annually using ANSI or other industry recognized standards. Pressure transducers shall have a drift stability of less than 3 psi over the operational period of the instrument and an accuracy of ± 5 psi. Sampling rates will be at least once every 5 seconds.

Longleaf CCS, LLC will deploy fiber optic cable on the outside of the long string casing to the bottom of the well for all above-zone monitoring wells. Fiber optic cable will enable continuous micro-seismic and geophysical monitoring through DAS and well integrity assurance and leak detection through DTS.

F.4. Above-Zone Observation Well Mechanical Integrity Testing

Longleaf CCS, LLC will conduct the tests presented below in **Table 11** periodically during the injection phase to verify external mechanical integrity in all above-zone monitoring wells. Demonstrating and maintaining the mechanical integrity of above-zone monitoring wells is also meant to satisfy the State Oil and Gas Board of Alabama regulatory guidelines.

Table 11. Showing MIT Test Description and Frequency at Above-Zone Monitoring Wells.

Test Description	Frequency During Injection Phase
Annulus Pressure Test	Every 5yrs
Annulus Pressure Monitoring	Continuous
Pulsed Neutron Capture (PNC) Log	Baseline before injection; 3yrs after injection begins; Every 5yrs thereafter
Distributed Temperature Sensing (DTS)	Continuous
Temperature Logging	Baseline before injection; 3yrs after injection begins; Every 5yrs thereafter
Ultrasonic Cement Bond Inspection Log	Once before injection

PNC logs will be run at least once prior to the start of CO_2 injection, 3 years after injection begins, and every five years thereafter until the well is plugged and abandoned. Following a baseline, subsequent logs can be compared to determine changes in fluid flow adjacent to the wellbore and detect any CO_2 leakage above the confining zone. A temperature log will be deployed in conjunction with PNC logging to further evaluate mechanical integrity.

Continuous DTS monitoring will provide additional comprehensive mechanical integrity confirmation by continuously monitoring for areas along the wellbore with anomalous changes in temperature. The annulus between the tubing and the long string of casing will be filled with brine and a corrosion inhibitor and a pressure gauge will continuously monitor the annular pressure.

F.5. Above-Zone Plume and Pressure Front Tracking

Direct plume and pressure front tracking cannot occur in above-zone monitoring wells because they will be completed in a formation above the confining layer. However, Longleaf CCS, LLC will deploy CO_2 detection and pressure monitoring strategies in the above-zone monitoring wells in order to detect any CO_2 leakage.

Longleaf CCS, LLC will conduct cased hole PNC logs in the above-zone monitoring wells to indirectly detect any CO_2. PNC logs will be utilized once before injection, 3 years after injection begins, and every five years thereafter until the above-zone monitoring wells are plugged and abandoned. Additionally, Longleaf CCS, LLC will conduct VSP surveys to monitor the geophysical environment and potentially image any CO_2 leaks. These VSPs will occur once before injection, 3 years after injection begins, and every five years thereafter until the above-zone monitoring wells are plugged and abandoned or site closure.

A bottomhole pressure gauge with continuous surface read-out data and pressure gauges in the tubing and annulus at the surface will provide direct pressure monitoring data. Any anomalous changes in pressure could signal the presence of CO_2 above the confining zone.

F.6. Above-Zone Groundwater and Geochemistry Monitoring

In each above-zone monitoring well, fluid sampling will occur at least three times prior to injection, quarterly for the first year of injection, and annually through the injection and post-injection site care periods. **Table 12** below lists the parameters to be monitored and the analytical methods Longleaf CCS, LLC will use to analyze formation fluid. Sampling, laboratory, and handling methods are described in the *QASP*.

Table 12: Summary of Analytical and Field Parameters for Above-Zone Monitoring Well Fluid Samples.

Parameters	Analytical Methods
Above-Zone Monitoring Wells- Upper Tuscaloosa Formation	
Cations: Al, Ba, Mn, As, Cd, Cr, Cu, Pb, Sb, Se, and Tl	ICP-MS, EPA Method 6020B[5] or EPA Method 200.8[6]
Cations: Ca, Fe, K, Mg, Na, and Si	ICP-OES, EPA Method 6010D[7] or EPA Method 200.7[8]
Anions: Br, Cl, F, NO_3, and SO_4	Ion Chromatography, EPA Method 300.0[9]
Isotopes: S13C of DIC	Isotope ratio mass spectrometry
Dissolved CO_2 Total Dissolved Solids Water Density Alkalinity pH (field) Specific conductance (field) Temperature (field)	Coulometric titration, ASTM D513-16[10] Gravimetry, APHA 2540C[11] Oscillating body method APHA 2320B[12] EPA 150.1[13] APHA 2510[14] Thermocouple

[5] U.S. EPA. 2014. "Method 6020B (SW-846): Inductively Coupled Plasma-Mass Spectrometry." Revision 2. Washington, DC.

[6] U.S. EPA. 1994. "Determination of Trace Elements in Waters and Wastes by Inductively Coupled Plasma – Mass Spectrometry." Revision 5.4. Environmental Monitoring Systems Laboratory Office of Research and Development U.S. Environmental Protection Agency, Cincinnati, Ohio.

[7] U.S. EPA. 2014. "Method 6010D (SW-846): Inductively Coupled Plasma-Optical Emission Spectrometry." Revision 4. Washington, DC.

[8] U.S. EPA. 1994. "Determination of Trace Elements in Waters and Wastes by Inductively Coupled Plasma – Atomic Emission Spectrometry." Revision 4.4. Environmental Monitoring Systems Laboratory Office of Research and Development U.S. Environmental Protection Agency, Cincinnati, Ohio.

[9] U.S. EPA. 1993. "Method 300.0: "Methods for the Determination of Inorganic Substances in Environmental Samples." Revision 2.1. Washington, DC.

[10] ASTM Standard D513-16. 1988 (2016). "Standard Test Methods for Total and Dissolved Carbon Dioxide in Water," ASTM International, West Conshohocken, PA. DOI: 10.1520/D0513-16, www.astm.org

[11] American Public Health Association (APHA), SM 2540 C, "Standard Methods for the Examination of Water and Wastewater", APHA-AWWA-WPCF, 20th Edition (SDWA) and 21st Edition (CWA).

[12] Method 2320 B, Standard Methods for the Examination of Water and Wastewater, APHA-AWWA-WPCF, 21st Edition, 1997.

[13] U.S. EPA. 1971 (1982). "Method 150.1: pH in Water by Electromagnetic Method", Cincinnati, OH.

[14] American Public Health Association (APHA), SM2510, 1992. Standard Methods for the Examination of Water and Wastewater", APHA-AWWA-WPCF, 18th Edition, 1992.

G. Deep USDW Well Monitoring

Deep USDW monitoring wells will be completed in the lowest most USDW at the Longleaf CCS Hub, identified as the Chickasawhay Formation at an approximate depth of 1,700 ft SS. Four deep USDW monitoring wells will be completed to monitor the geochemistry of the Chickasawhay Formation fluid and detect any CO_2 leakage. **Figure 1** below displays the locations of these four deep USDW monitoring wells.

Longleaf CCS, LLC considered geologic site data, the presence of artificial penetrations, community impact, and the results of an extensive reservoir modeling effort to determine the location for deep USDW monitoring wells that will best ensure non-endangerment to USDWs and local communities. The placement of the four deep USDW monitoring wells is based on an internal risk assessment and shown in **Figure 1**.

G.1. Placement of Deep USDW Wells

Deep USDW monitoring well UOB#3 will be placed in the middle of the four planned injection wells at the Longleaf CCS Hub where modeling has indicated that pressure will increase the greatest in the Paluxy injection interval during the injection period. Additional deep USDW monitoring wells UOB#1, UOB#2, and UOB#4 are placed in the far-field where the CO_2 plume is expected to migrate over time, near the edges of the AoR.

Existing well penetrations are not expected to be a risk for CO_2 leakage at the Longleaf CCS Hub because there are no existing wells within the AoR.

G.2. Deep USDW Well Monitoring Activities

In each deep USDW monitoring well, fluid sampling will occur at least three times prior to injection and occur annually through the injection and post-injection site care periods. **Table 13** below lists the parameters to be monitored and the analytical methods Longleaf CCS, LLC will use to analyze formation fluid. Sampling, laboratory, and handling methods are described in the *QASP*.

Table 13: Summary of Analytical and Field Parameters for Deep USDW Formation Fluid Samples.

Parameters	Analytical Methods
Deep USDW Monitoring Wells- Chickasawhay Formation	
Cations: Al, Ba, Mn, As, Cd, Cr, Cu, Pb, Sb, Se, and Tl	ICP-MS, EPA Method 6020B[15] or EPA Method 200.8[16]
Cations: Ca, Fe, K, Mg, Na, and Si	ICP-OES, EPA Method 6010D[17] or EPA Method 200.7[18]
Anions: Br, Cl, F, NO_3, and SO_4	Ion Chromatography, EPA Method 300.0[19]
Isotopes: S13C of DIC	Isotope ratio mass spectrometry
Dissolved CO_2 Total Dissolved Solids Water Density Alkalinity pH (field) Specific conductance (field) Temperature (field)	Coulometric titration, ASTM D513-16[20] Gravimetry, APHA 2540C[21] Oscillating body method APHA 2320B[22] EPA 150.1[23] APHA 2510[24] Thermocouple

[15] U.S. EPA. 2014. "Method 6020B (SW-846): Inductively Coupled Plasma-Mass Spectrometry." Revision 2. Washington, DC.

[16] U.S. EPA. 1994. "Determination of Trace Elements in Waters and Wastes by Inductively Coupled Plasma – Mass Spectrometry." Revision 5.4. Environmental Monitoring Systems Laboratory Office of Research and Development U.S. Environmental Protection Agency, Cincinnati, Ohio.

[17] U.S. EPA. 2014. "Method 6010D (SW-846): Inductively Coupled Plasma-Optical Emission Spectrometry." Revision 4. Washington, DC.

[18] U.S. EPA. 1994. "Determination of Trace Elements in Waters and Wastes by Inductively Coupled Plasma – Atomic Emission Spectrometry." Revision 4.4. Environmental Monitoring Systems Laboratory Office of Research and Development U.S. Environmental Protection Agency, Cincinnati, Ohio.

[19] U.S. EPA. 1993. "Method 300.0: "Methods for the Determination of Inorganic Substances in Environmental Samples." Revision 2.1. Washington, DC.

[20] ASTM Standard D513-16. 1988 (2016). "Standard Test Methods for Total and Dissolved Carbon Dioxide in Water," ASTM International, West Conshohocken, PA. DOI: 10.1520/D0513-16, www.astm.org

[21] American Public Health Association (APHA), SM 2540 C, "Standard Methods for the Examination of Water and Wastewater", APHA-AWWA-WPCF, 20th Edition (SDWA) and 21st Edition (CWA).

[22] Method 2320 B, Standard Methods for the Examination of Water and Wastewater, APHA-AWWA-WPCF, 21st Edition, 1997.

[23] U.S. EPA. 1971 (1982). "Method 150.1: pH in Water by Electromagnetic Method", Cincinnati, OH.

[24] American Public Health Association (APHA), SM2510, 1992. Standard Methods for the Examination of Water and Wastewater", APHA-AWWA-WPCF, 18th Edition, 1992.

H. Shallow USDW and Surface Monitoring

Shallow USDW monitoring wells at the Longleaf CCS Hub will be completed within a near-surface freshwater source to monitor the geochemistry of the formation fluid and detect any CO_2 leakage. Ten shallow USDW monitoring wells will be constructed, each on an existing well pad, as shown in **Figure 1**.

In each shallow USDW monitoring well, fluid sampling will occur at least three times prior to injection to establish a baseline and repeated annually through the injection and post-injection site care periods. **Table 14** below lists the parameters to be monitored and the analytical methods Longleaf CCS, LLC will use to analyze shallow groundwater. The sampling, laboratory, and handling methods are described in the *QASP*.

Table 14: Summary of Analytical and Field Parameters for Ground Water Samples.

Parameters	Analytical Methods
Shallow USDW Monitoring Wells (Near Surface)	
Cations: Al, Ba, Mn, As, Cd, Cr, Cu, Pb, Sb, Se, and Tl	ICP-MS, EPA Method 6020B[25] or EPA Method 200.8[26]
Cations: Ca, Fe, K, Mg, Na, and Si	ICP-OES, EPA Method 6010D[27] or EPA Method 200.7[28]
Anions: Br, Cl, F, NO_3, and SO_4	Ion Chromatography, EPA Method 300.0[29]

[25] U.S. EPA. 2014. "Method 6020B (SW-846): Inductively Coupled Plasma-Mass Spectrometry." Revision 2. Washington, DC.

[26] U.S. EPA. 1994. "Determination of Trace Elements in Waters and Wastes by Inductively Coupled Plasma – Mass Spectrometry." Revision 5.4. Environmental Monitoring Systems Laboratory Office of Research and Development U.S. Environmental Protection Agency, Cincinnati, Ohio.

[27] U.S. EPA. 2014. "Method 6010D (SW-846): Inductively Coupled Plasma-Optical Emission Spectrometry." Revision 4. Washington, DC.

[28] U.S. EPA. 1994. "Determination of Trace Elements in Waters and Wastes by Inductively Coupled Plasma – Atomic Emission Spectrometry." Revision 4.4. Environmental Monitoring Systems Laboratory Office of Research and Development U.S. Environmental Protection Agency, Cincinnati, Ohio.

[29] U.S. EPA. 1993. "Method 300.0: "Methods for the Determination of Inorganic Substances in Environmental Samples." Revision 2.1. Washington, DC.

Parameters	Analytical Methods
Dissolved CO_2	Coulometric titration, ASTM D513-16[30]
Total Dissolved Solids	Gravimetry, APHA 2540C[31]
Water Density	Oscillating body method
Alkalinity	APHA 2320B[32]
pH (field)	EPA 150.1[33]
Specific conductance (field)	APHA 2510[34]
Temperature (field)	Thermocouple

The need for surface monitoring, such as soil gas and atmospheric detectors, will be continually evaluated throughout the operational phase of the project. Given Longleaf CCS, LLC's current understanding of the subsurface environment and existing well penetrations, any endangerment to USDWs would likely be captured first by the deeper well monitoring protocols and activities set forth by this *Testing and Monitoring Plan*. As such, a network of soil-gas and atmospheric monitoring stations is not proposed at this time. Longleaf CCS, LLC will submit a separate EPA Monitoring, Reporting and Verification (MRV) Plan and comply with all monitoring and reporting requirements under Subpart RR of the Greenhouse Gas Reporting Program.

I. Seismicity and Fault Monitoring

As part of the geologic characterization of the Longleaf CCS Hub, six 2D seismic lines were acquired and interpreted from Seismic Exchange Inc. The objectives of the seismic analysis were as follows:

- To demonstrate the areal extent and continuity of the prospective CO_2 storage reservoir sands.
- To demonstrate the lateral continuity of the regional confining units.

[30] ASTM Standard D513-16. 1988 (2016). "Standard Test Methods for Total and Dissolved Carbon Dioxide in Water," ASTM International, West Conshohocken, PA. DOI: 10.1520/D0513-16, www.astm.org

[31] American Public Health Association (APHA), SM 2540 C, "Standard Methods for the Examination of Water and Wastewater", APHA-AWWA-WPCF, 20th Edition (SDWA) and 21st Edition (CWA).

[32] Method 2320 B, Standard Methods for the Examination of Water and Wastewater, APHA-AWWA-WPCF, 21st Edition, 1997.

[33] U.S. EPA. 1971 (1982). "Method 150.1: pH in Water by Electromagnetic Method", Cincinnati, OH.

[34] American Public Health Association (APHA), SM2510, 1992. Standard Methods for the Examination of Water and Wastewater", APHA-AWWA-WPCF, 18th Edition, 1992.

- To evaluate local structure and identify faults that may exist in the injection zone and confining units.

The seismic interpretation confirmed the continuity of both the Paluxy Formation, the targeted injection interval, and the Tuscaloosa Marine Shale, the regional confining unit. No faults or significant structural features that may disrupt the storage complex geology were found within the AoR.

East of the AoR and the Longleaf CCS Hub, there is the Hatter's Pond Fault that forms the eastern edge of the Mobile Graben (See section *B.3. Faults and Fractures* in the *Project Narrative*). The CO_2 plume is not expected to reach or interact with this inactive fault. Two in-zone monitoring wells have been placed on the east side of the Longleaf CCS Hub in order to monitor the location of the plume and pressure front in the area approaching the Mobile Graben. These wells will be equipped with pressure monitors and fiber optic cables to continuously monitor pressure and deploy DAS. The downhole pressure gauges will monitor for evidence of elevated pressure in the injection zone. DAS will monitor for any unusual micro-seismic events that may be warning signs for a loss of well integrity or locally induced seismicity.

J. Updating the Testing and Monitoring Plan

Pursuant to 40 CFR 146.90(j), this Plan will be reviewed at least once every five years after the start of injection until site closure. The Plan will be reviewed within one year of any plume and pressure front assessment or after any significant changes to the facility such as addition of injection wells. All reviews and updates will incorporate operational and monitoring data collected during the construction and injection periods.

Any amendments to this Plan made during the review process will be provided to the UIC Program Director for approval before their incorporation into the final update. If no amendments to the Plan are made during the review, a justification will be provided to the UIC Program Director.

K. Reporting

This section outlines the content and timing associated with report delivery to the UIC Program Director pursuant to the guidelines established in 40 CFR 146.91.

K.1. Semi-Annual Reporting

Per 40 CFR 146.91(a), Longleaf CCS, LLC will provide the UIC Program Director with semi-annual reports containing the following.

- Any changes to the physical/chemical characteristics of the CO_2 stream.
- The monthly averages, minimums and maximums recorded for the operating injection pressure, injection flow rate, injection volume or mass, and annular pressure.
- A description of any event where operating annulus or injection pressure limits were exceeded.
- A description of any shut down event triggered by injection well operating alarms and a description of the response taken.
- The monthly volume or mass of CO_2 injected over the current reporting period and cumulative volume or mass of CO_2 injected since the start of injection.

- The volume of annulus fluid added each month over the reporting period, if any.
- Any data collected or notable results from the implementation of the *Testing and Monitoring Plan*.

K.2. Reporting within 30 Days

Per 40 CFR 146.91(b), Longleaf CCS, LLC will provide the UIC Program Director with the following results from an injection well within 30 days of occurrence.

- The results of any MIT.
- The results of any well workover.
- The results of any other injection well test.

K.3. Reporting within 24 Hours

Per 40 CFR 146.91(c), Longleaf CCS, LLC will report the following events within 24 hours of occurrence.

- Any evidence that the injected CO_2 stream or associated pressure front may cause an endangerment to a USDW.
- Any noncompliance with a permit condition, or malfunction of the injection system, which may cause fluid migration into or between USDWs.
- Any triggering of a shut-off system downhole or at surface.
- Any failure to maintain mechanical integrity.

K.4. Advanced Notice of Activities and Document Retention

Per 40 CFR 146.91(d), Longleaf CCS, LLC will provide written notice to the UIC Program Director within 30 days in advance of the following activities at an injection well.

- Any planned well workover.
- Any planned stimulation activities other than stimulation for formation testing conducted under the initial collection of geologic information.

- Any other planned test of the injection well by Longleaf CCS, LLC.

Per 40 CFR 146.91(f), Longleaf CCS, LLC will retain records in the following manner.

- All site characterization data will be retained throughout the life of the geologic sequestration project and for at least 10 years following site closure.
- Data on the nature and composition of all injected fluids will be retained for at least 10 years after site closure.
- Any monitoring data collected through the *Testing and Monitoring Plan* will be retained for at least 10 years after it is collected.
- Well plugging reports and all post-injection site care data will be retained for at least 10 years after site closure.