TESTING AND MONITORING PLAN
40 CFR 146.90

FRONT RANGE STORAGE COMPLEX

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List of Acronyms and Abbreviations

Ag = Silver
Al = Aluminum
AoR = area of review
As = Arsenic
ASTM = ASTM International
B = Boron
Ba = Barium
bbl = barrels
Be = Beryllium
bpd = barrels per day
Br = Bromide
Ca = Calcium
$CaCO_3$ = Calcium carbonate
Cd = Cadmium
Cl = Chloride
Co = Cobalt
CO_2 = carbon dioxide
Cr = Chromium
CSS = Carbon Storage Solutions, LLC
Cu = Copper
$\delta^{13}C$ of DIC = Ratio of two stable carbon isotopes in dissolved inorganic carbon
DTS = distributed thermal sensing
ELAP = Environmental Laboratory Accreditation Program
F = Fluoride
Fe = Iron
ft/min = feet per minute
ft TVD = feet total vertical depth
gal = gallon(s)
GS = geologic sequestration
GPSA = Gas Processors Supplier Association
H_2S = hydrogen sulfide
IARF = Infinite-acting radial flow
ICP = Inductively coupled plasma
ICP-MS = Inductively coupled plasma mass Spectrometry
ISBT = International Society of Beverage Technologies
K = Kelvin
lb = pound(s)
lb/ft^3 = pounds per cubic feet
lbmol = pound mole(s)
lb/MMSCF = pounds per million standard cubic feet
Li - Lithium
Mg = Magnesium
mi^2 = square mile(s)
MIT = mechanical integrity test
M_L = local magnitude
MMA = maximum monitoring area
Mn = Manganese
N = Nitrogen
Na = Sodium
NACE = NACE International
NDIR = non-dispersive infra-red
Ni = Nickel
NO_3 = Nitrate
Pb = Lead
PISC = Post-Injection Site Care
ppmw = parts per million, weight
ppmv = parts per million, volume
psi = pound-force per square inch
psia = pound-force per square inch, absolute
psig = pound-force per square inch, gauge
QASP = Quality Assurance and Surveillance Plan
SAR = Sodium Adsorption Ratio
Sb = Antimony
Se = Selenium
Si = Silicon
SiO_2 = Silicon dioxide
SM = Standard Method
SO_4 = Sulfate
Sr = Strontium
Tl = Thallium
UIC = Underground Injection Control
UNS = unified numbering system
US EPA = United States Environmental Protection Agency
USDW = Underground Source of Drinking Water
USGS = United States Geological Survey
V = Vanadium
vol % = percent volume
VSP = vertical seismic profile
Zn = Zinc

E.1. Summary

This Testing and Monitoring Plan describes how Carbon Storage Solutions, LCC (CSS) will monitor the project site pursuant to 40 CFR 146.90. In addition to demonstrating the well is operating as planned, the carbon dioxide (CO_2) plume and pressure front are moving as predicted, and that there is no endangerment to Underground Source of Drinking Water (USDW), the monitoring data will be used to validate and adjust the geological models used to predict the distribution of the CO_2 within the storage zone to support area of review (AoR) re-evaluations and a non-endangerment demonstration.

The plan is designed with a suite of methods covering:

- Well Integrity – An integrated set of testing and monitoring elements are utilized to assure mechanical integrity for the geologic sequestration (GS) project wells.
- Operational Testing and Monitoring During Injection – A comprehensive program consisting of: Analysis of CO_2 Stream, Monitoring of Operational Parameters, Corrosion Monitoring, and Pressure Fall-Off Testing.
- Groundwater Quality and Geochemical Monitoring – A series of monitoring stations have been established across the project site to support testing of groundwater quality and geochemical monitoring of groundwater key locations above the primary upper confining zone.
- Plume and Pressure Front Tracking – Plume tracking is performed by direct measurements on injection zone fluid samples from Front Range 2-1, plus indirect geophysical measurements using time-lapse vertical seismic profiles. Pressure front tracking is performed by direct measurement of downhole pressures at Front Range 1-1 and Front Range 2-1.
- Additional Testing and Monitoring – Implementation of Soil Gas Monitoring and Surface CO_2 Monitoring programs to improve the ability to detect potential leaks of CO_2 to surface, plus implementation of a Seismic Monitoring program for timely detection of seismic activity.

Results of the testing and monitoring activities described herein may trigger action according to the Emergency and Remedial Response Plan.

E.2. Overall Strategy and Approach for Testing and Monitoring

The overall strategy and approach for testing and monitoring is to utilize a comprehensive set of test methods to obtain the data needed to monitor the GS project per the requirements of 40 CFR 146.90, demonstrate non-endangerment to USDWs, and provide sufficient data on site-specific system behavior to support decision making at project milestones.

Figure E.2-1 is a simplified illustration showing how potential project risks vary over the course of a GS project, along with a summary timeline for testing and monitoring activities during the

GS project periods. All testing and monitoring activities in this plan apply to the Injection period of the project. This plan also covers several testing and monitoring activities that begin prior to the Injection period in order to obtain baseline data needed for interpretation of data collected during later periods (e.g., data on groundwater quality above the upper confining zone); however, see the Pre-Operational Testing Program for descriptions of logging and testing of Front Range 1-1 and Front Range 2-1 that occur prior to the Injection period.

This plan also covers testing and monitoring activities that extend into the Post-Injection Site Care (PISC) period when project risk begins to fall. To simplify discussion on frequency of testing and monitoring during PISC, the PISC will be divided into: (a) an Initial PISC period lasting for two years after cessation of CO_2 injection during which time the frequency of testing and monitoring will be carried over from the Injection period since project risk remains relatively high, and (b) a Maintenance PISC period starting at the end of the Initial PISC period and ending at Site Closure during which time the types and frequency of testing and monitoring can be reduced since project risk is comparatively low. For example, above upper confining zone groundwater geochemical monitoring is extended into the PISC period to ensure low endangerment risk to USDWs, with frequency of sampling during the Initial PISC period remaining at annual per extension of the frequency at the end of the Injection period, moving to 5-year intervals during the Maintenance PISC period.

Figure E.2-1. Testing and Monitoring Activities During Different Periods of a GS Project in Relation to Potential Project Risk
(From: EPA 2013)

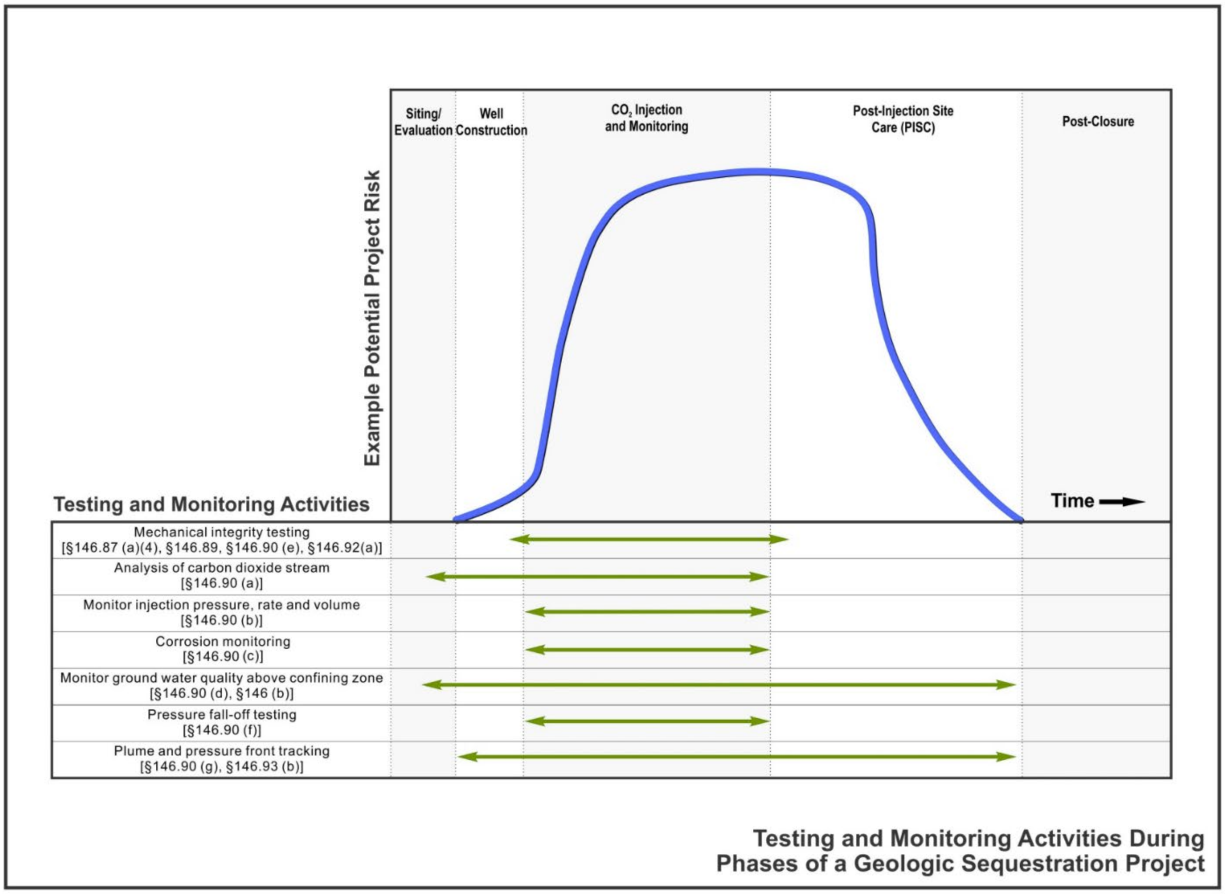


Table E.2-1 provides a summary of the testing and monitoring plan by category/sub-category along with a general schedule for each test method. A primary test method is given for each sub-category that directly addresses the requirements of 40 CFR 146.90. In addition, the plan is designed with a suite of complementary methods. Analyses of data from these complementary methods are used to corroborate analysis results from the primary test method and/or provide redundancy in the event of a primary test method failure.

Table E.2-1. Summary of Testing and Monitoring Plan

Category	Parameter	Location	Primary Test Method					Complementary Methods
			Testing Frequency by Project Period				Method	
			Pre-Injection	Injection	Initial PISC	Maintenance PISC		
Well Integrity	Internal Mechanical Integrity	Front Range 1-1	Not Applicable	Continuous	Not Applicable	Not Applicable	Monitoring of Operational Parameters	1) Annulus Pressure Test 2) Corrosion Monitoring
		Front Range 1-1	Once	Not Applicable	Not Applicable	Not Applicable	Annulus Pressure Test	-
	External Mechanical Integrity	Front Range 1-1, Front Range 2-1	Once	Annual	Annual	Every 5 years	Oxygen activation log, Temperature Log, or Noise Log	1) Monitoring of Operational Parameters 2) Corrosion Monitoring
Operational Testing and Monitoring	Analysis of CO_2 Stream	Front Range 1-1	Not Applicable	Chemical: Quarterly; Isotope: Every 5 yr	Not Applicable	Not Applicable	Lab analysis of grab samples	Monitoring of Operational Parameters
	Monitoring of Operational Parameters	Front Range 1-1	Not Applicable	Continuous	Not Applicable	Not Applicable	Measurement of injectate parameters, measurement of annulus pressure and fluid added	Automatic alarms and shut-down systems
	Corrosion Monitoring	Front Range 1-1	Not Applicable	Quarterly	Not Applicable	Not Applicable	Corrosion coupon testing	1) Internal MIT 2) External MIT
	Pressure Fall-Off	Front Range 1-1	Once	Every 5 years	Not Applicable	Not Applicable	Pressure fall-off test	Monitoring of Operational Parameters

Category	Parameter	Location	Primary Test Method					Complementary Methods
			Testing Frequency by Project Period				Method	
			Pre-Injection	Injection	Initial PISC	Maintenance PISC		
Groundwater Quality and Geochemical Monitoring	Groundwater Quality	MMA	Continuous	Continuous	Continuous	Data Logger Only	Monitor network of shallow groundwater wells	Geochemical & isotope analyses of groundwater samples
Groundwater Quality and Geochemical Monitoring	Geochemical Monitoring	MMA	Quarterly, to establish baseline	Quarterly/ Semi-Annual/ Annual	Annual	Every 5 years	Geochemical & isotope analyses of groundwater samples	Monitor network of shallow groundwater wells
Plume and Pressure Front Tracking	Plume Tracking (Direct)	Front Range 2-1	Once	See Testing & Monitoring Plan Text	Not Applicable	Not Applicable	Geochemical & isotope analyses of injection zone fluid samples	Computational modeling
Plume and Pressure Front Tracking	Plume Tracking (Indirect)	MMA	Once	Every 5 years, plus one at end of period	Not Applicable	Every 5 years from start of PISC, plus one at end of period	Time-lapse VSP surveys	Computational modeling
Plume and Pressure Front Tracking	Pressure Front Tracking (Direct)	Front Range 1-1	Continuous (upon installation)	Continuous	Continuous	Continuous (Data Logger Only)	Downhole pressure measurement	Computational modeling
Plume and Pressure Front Tracking	Pressure Front Tracking (Direct)	Front Range 2-1	Continuous (upon installation)	Continuous	Continuous	Continuous (Data Logger Only)	Downhole pressure measurement	Computational modeling

Category	Parameter	Location	Primary Test Method					Complementary Methods
			Testing Frequency by Project Period				Method	
			Pre-Injection	Injection	Initial PISC	Maintenance PISC		
Additional Project-Specific Testing & Monitoring	Soil Gas Monitoring	MMA	Continuous	Continuous	Continuous	Data Logger Only	Continuous CO_2 sensor	1) Lab analysis of grab samples 2) CO_2 efflux measurements
			Quarterly (baseline)	Quarterly/ Semi-Annual/ Annual	Annual	Every 5 years	Lab analysis of grab samples	1) Continuous CO_2 sensor 2) CO_2 efflux measurements
			Quarterly (baseline)	Quarterly/ Semi-Annual/ Annual	Annual	Every 5 years	CO_2 efflux measurements	1) Continuous CO_2 sensor 2) Lab analysis of grab samples
	Surface CO_2 Monitoring	Front Range 1-1, Front Range 2-1	Not Applicable	Continuous	Continuous	Data Logger Only	Atmospheric CO_2 sensor at wellhead	Field inspection of wellhead and surface piping
			Not Applicable	Quarterly/ Semi-Annual/ Annual	Annual	Every 5 years	Field inspection of wellhead and surface piping	Atmospheric CO_2 sensor at wellhead
	Seismic Monitoring	MMA	Continuous (baseline)	Continuous	Continuous	Not Applicable	Monitor regional seismic network	-

MIT = mechanical integrity test
MMA = maximum monitoring area

The general schedule is designed to provide testing and monitoring results in a timely manner, while being judicious in the need to interrupt operations during the Injection period. The ethanol plant producing the CO_2 source undergoes an annual scheduled maintenance outage for several days each year during which time CO_2 is not available for injection. This testing and monitoring plan is designed around this annual scheduled CO_2 supply outage. The injection well may either be shut-in or undergo a workover during the annual scheduled CO_2 supply outage; thus scheduling of testing and monitoring activities conveniently falls into the following categories:

- Continuous, monthly, and quarterly testing and monitoring activities are performed at the indicated frequency, independent of the schedule for well shut-ins or workovers since all of these activities can be performed without interrupting injection operations;
- Annual and 5-year testing and monitoring activities that require a well shut-in or workover are performed during the annual scheduled CO_2 supply outage; or
- Annual and 5-year testing and monitoring activities that do not require a well shut-in or workover are performed at the indicated frequency, independent of the schedule for well shut-ins or workovers since all of these activities can be performed without interrupting injection operations.

The spatial distribution of this plan covers the three-dimensional volume of the AoR as delineated in the Area of Review and Corrective Action Plan. In addition, this plan covers the MMA, where the MMA is defined as the areal extent of the AoR plus a ½-mile buffer zone. Figure E.2-2 is a surface map that displays the areal extent of the AoR, the MMA, and the general locations of the project testing and monitoring stations.

This plan is tailored to the regional and local site characterization and risk profile of this particular GS project. The testing and monitoring requirements of 40 CFR 146.90 result in a complementary suite of methods that address most aspects needed to verify a GS project is operating as permitted and is not endangering USDWs. However, a site-specific risk assessment for this GS project identified CO_2 leakage to the surface and seismic events as scenarios not fully addressed by the minimum requirements of 40 CFR 146.90. Thus, this plan contains additional testing and monitoring elements to identify and quantify potential CO_2 leakage to the surface across the MMA (i.e., Soil Gas Monitoring, Surface Air Monitoring), and this plan also contains a Seismic Monitoring program to identify and mitigate risks associated with seismic events.

[redacted]

E.2.1. Quality Assurance Procedures

The Quality Assurance and Surveillance Plan (QASP) provided as Attachment E.I of the Testing and Monitoring Plan includes and describes the project-specific quality assurance procedures to be followed pursuant to 40 CFR 146.90(k).

E.2.2. Reporting Procedures

CSS will report the results of all testing and monitoring activities to the United States Environmental Protection Agency (US EPA) in compliance with the requirements set forth under 40 CFR 146.91.

E.3. Internal Mechanical Integrity [40 CFR 146.87(a)(4)(i), 40 CFR 146.90(b)]

Monitoring of operational parameters (see Section E.6) is the primary method to ensure internal mechanical integrity of Front Range 1-1 during the Injection period, conforming to the requirements of 40 CFR 146.90(b). In addition, an annulus pressure test (aka tubing-casing annulus pressure test) will be conducted on Front Range 1-1 during the Pre-Injection period to confirm internal mechanical integrity in conformance with 40 CFR 146.87(a)(4)(i). This Pre-Injection period test will be conducted after the well has been constructed and all well logs have been conducted.

A standard annulus pressure test procedure will be followed patterned off the procedure provided by the US EPA (Attachment 1 – Standard Annulus Pressure Test, in EPA 2008). In summary, the steps are:

1. The annulus will be filled with liquid and the temperature along the entire length of the tubing (as measured by the distributed thermal sensing [DTS] system) will be allowed to stabilize either by a well shut-in or maintaining stabilized injection before and during the test (i.e., continuous injection at a constant rate and constant injection fluid temperature).
2. After temperature stabilization, the annulus will be pressurized to a surface pressure equal to or greater than 110% times the sum of the anticipated maximum operating pressure of the internal tubing at wellhead plus 100 pounds per square inch (psi) to account for the minimum pressure difference between the annulus and internal tubing during normal injection operations. Once pressurized for this test, the annular system will be isolated from the source of pressure and any sources of additional liquid.
3. The annulus system must remain isolated for a testing period of no less than 60 minutes unless a shorter time is deemed adequate upon completion of the final system design. Pressure measurements will be recorded at 5-minute intervals during isolation unless a different interval is deemed acceptable upon completion of the final design.
4. After the test is completed, the valve to the annulus should be opened and liquid flow from the annulus observed and measured using a graduated bucket/tank.

The data obtained from the standard annulus pressure test will be interpreted as follows:

1. If the annulus pressure changed by less than 3% of the test pressure (gain or loss) then the well has demonstrated internal mechanical integrity.
2. Validation of test results using the procedure published by US EPA (Attachment 1 – Standard Annulus Pressure Test, in EPA 2008) to evaluate of the amount of liquid returned.

E.4. External Mechanical Integrity [40 CFR 146.87(a)(4), 40 CFR 146.89(c), 40 CFR 146.90(e)]

CSS will conduct at least one of the external MITs presented in Table E.4-1 periodically to verify external mechanical integrity of Front Range 1-1 over its service life as required at 146.87(a)(4), 146.89(c), and 146.90. In addition, these same tests and testing frequency will be utilized to verify external mechanical integrity of Front Range 2-1 over its service life even though the Class VI regulations do not strictly require external mechanical integrity testing for monitoring wells.

Table E.4-1. External MIT Summary

Test Description	Tool Type
Oxygen Activation Log	Wireline
Temperature Log	DTS or Wireline
Noise Log	Wireline

E.4.1. Testing Location and Frequency

The frequency of testing for Front Range 1-1 and Front Range 2-1 will be: at least once during Pre-Injection, annual during Injection, annual during the Initial PISC period, and once every five years during the Maintenance PISC period. Testing for Front Range 1-1 will occur during planned shut-ins or workovers and will utilize the DTS (preferred) or any of the other methods identified in Table E.4-1. Testing for Front Range 2-1 will occur at the indicated frequency and will utilize the DTS (preferred) or any of the other methods identified in Table E.4-1. The Pre-Injection tests will use a temperature log in order to provide a baseline for comparison with any future temperature logs taken during Injection or PISC periods.

E.4.2. Testing Details

Pass/fail results from external MITs conducted on Front Range 1-1 will be corroborated with analysis of the Monitoring of Operational Parameters data (annulus fluid pressure, annulus fluid volume added) and data from the Corrosion Monitoring program. Pass/fail results from external MITs conducted on Front Range 2-1 will be corroborated with data from the Corrosion Monitoring program.

E.4.2.1. Oxygen Activation Log

An oxygen activation log is based on the ability of a wireline tool to emit high-energy neutrons that penetrate the casing and cement, converting the oxygen in water molecules outside the wellbore into N^{16} – an unstable isotope of nitrogen that undergoes beta decay with a half-life of 7.1 seconds, and generating high-energy gamma rays during beta decay of N^{16}. The resulting gamma rays easily re-penetrate the casing and cement and are measured by gamma ray detectors in the wireline tool, thus allowing the measurement of the direction and speed of water movement around the outside of the casing.

An oxygen activation log can be conducted on a well containing tubing using a slimline tool provided any injection is occurring close to the normal rate and there are minimal rate and pressure fluctuations during logging. The tool is to be calibrated and operated per the recommendations of the service provider and tool manufacturer. Calibration typically involves conducting a baseline gamma ray log and casing collar locator log from the top of the injection zone to the surface to determine naturally occurring background radiation, then taking a stationary measurement in a “no vertical flow behind the casing” section to zero the instrument.

At a minimum, stationary readings will be taken after the logging tool reaches each of the targeted depth intervals designated below and allowed to stabilize for at least 15 minutes (See Figure A.I.5-2 in Site Characterization for depths):

- Base of the lowermost USDW
- Top of the regional seal
- Tops of secondary upper confining zones
- Top of the primary upper confining zone

A potential loss of external mechanical integrity is indicated when the gamma ray measurements detect a difference between the expected (static) and measured gamma ray count rate profiles. The flow velocity is determined by measuring the time that activated water passes by a detector. External mechanical integrity is indicated when measured water speed at all locations are below a threshold of 2 feet per minute (ft/min) (Attachment 7, in EPA 2008). To minimize false positives, all measurement locations that indicate a water flow equal to or greater than 2 ft/min will be confirmed by measurements at several nearby depths (within 50 feet of original stationary location) and/or confirmed by measurements at the original stationary location under a minimum of 3 varying injections rates: 75%, 50%, and 25% of the maximum permitted injection rate (Attachment 7, in EPA 2008). Any failure in external MIT indicated by an oxygen activation log will be further confirmed using another approved external MIT method prior to taking measures to remedy the situation.

See Table E.I.1-15 for detailed information on the oxygen activated logging tool and its measurement specifications (e.g., range, precision, spatial resolution).

E.4.2.2. Temperature Log

A temperature log for external MIT purposes is based on the principle that fluid leaking from the well bore will cause a temperature anomaly in the formation adjacent to the well bore since the leaking fluid will, in most cases, be of a different temperature compared to native fluids at a given depth. Temperature logging for external MIT purposes during the Injection period are run after the well has been shut-in to allow for temperature equilibration. The US EPA (EPA 2013) states that 36 hours is usually a sufficient shut-in period for temperatures within the well bore to move toward static geothermal conditions. If there has been a leak of fluid out of the well, the temperature within the well bore at this location will be measured as an anomaly because the temperature of the surrounding formation will have been modified by the leaking fluid.

Front Range 1-1 is equipped with a continuously monitored DTS fiber optic system connected to the outside of the injection tubing. During normal injection operations, the DTS system provides temperature measurements along the length of the tubing that are mostly representative of the CO_2 stream. However, when the well is shut-in, the DTS provides temperature measurements that are representative of the formation temperature due to conductive heat transfer from the formation into the annulus fluid. Alternatively, a continuously moving wireline tool can be used to carry out the temperature log measurements.

Front Range 2-1 is equipped with a continuously monitored DTS fiber optic system cemented to the outside of the casing, thus the DTS provides temperature measurements representative of the formation. Alternatively, a continuously moving wireline tool can be used to carry out the temperature log measurements.

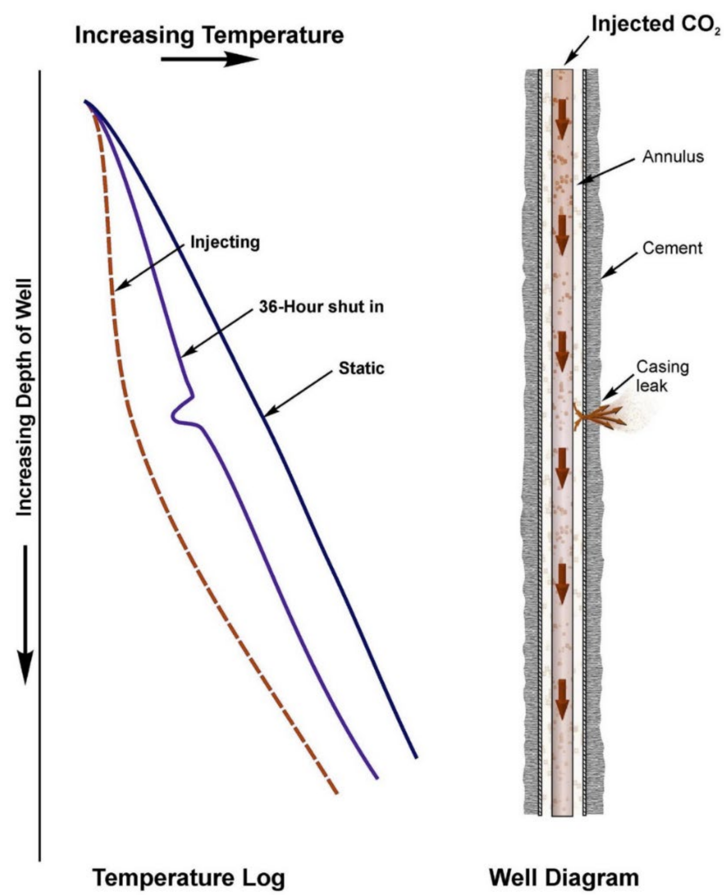
Temperature logs for both Front Range 1-1 and Front Range 2-1 will be conducted prior to start of injection to establish baseline static geothermal conditions. These baseline logs will be conducted long after drilling of the wells since temperature effects due to circulation and infiltration of drilling fluid can persist for several weeks or months after drilling is complete (EPA 2013).

Figure E.4-1 illustrates a static geothermal temperature profile, with comparison to a hypothetical example of a temperature log taken on an operating well after a 36-hour shut-in period. The anomaly in the temperature log of this hypothetical example aligns with the location of the casing leak. Actual temperature logs taken for this project that have an absence of temperature anomalies will constitute a “pass” for the external MIT. Actual temperature logs containing one or more anomalies suggest a potential "fail" for the external MIT. Any failure in external MIT indicated by a temperature log will be further confirmed using another approved external MIT method prior to taking measures to remedy the situation.

See Section E.I.1.4 of the QASP for detailed information on the temperature logging tool and its measurement specifications (e.g., range, precision, spatial resolution).

Figure E.4-1. Temperature Log Showing the Detection of a Casing Leak

Not to Scale (From: EPA 2013)

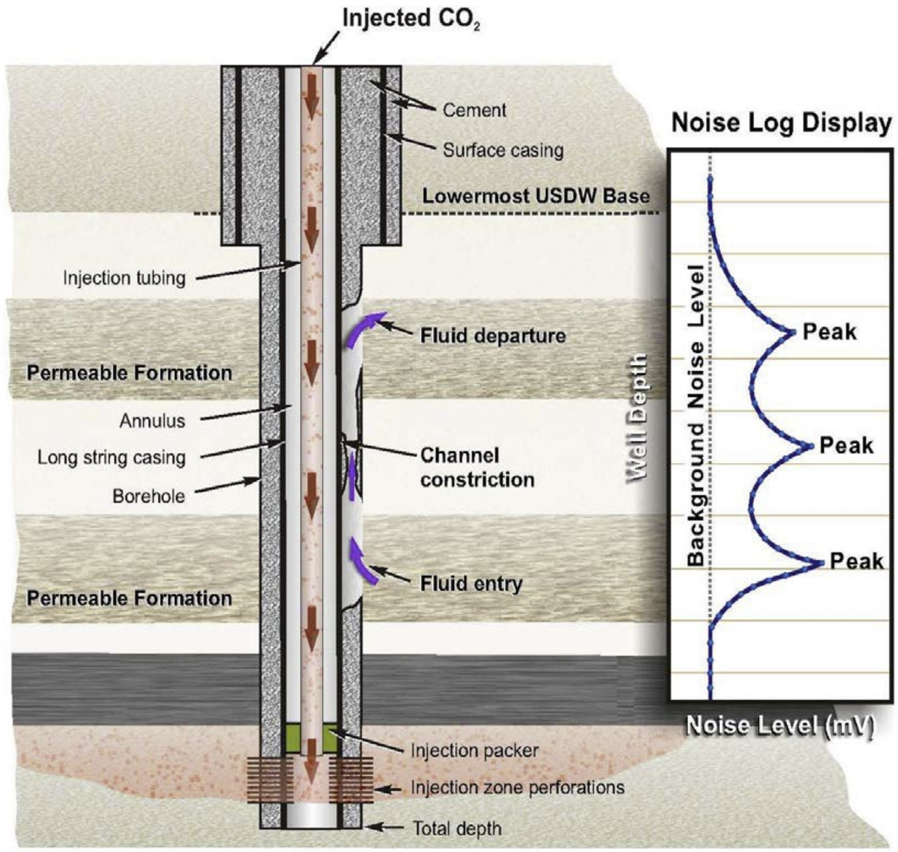


E.4.2.3. Noise Log

A noise log utilizes the principle that fluid flowing through channels in cement along the exterior of a wellbore usually results in the generation of some turbulence, creating sonic energy in audible frequency ranges that can be measured using a wireline tool containing very sensitive microphones, see Figure E.4-2. Noise logging can be conducted on a well with tubing using a slimline tool, and the log can be conducted while injecting.

Figure E.4-2. Noise Log Showing Detection of Fluid Flow in Cement Channels

Not to scale (From EPA 2013)



Noise log measurements are done in stationary mode. A reconnaissance mode can be used to identify general locations with higher-than-expected noise levels, followed by a series of stationary measurements to identify the exact location of the sonic energy. The US EPA recommendation for measurement intervals will be followed, starting with a coarse grid of measurements at 100-foot intervals, followed by 20-foot intervals within any coarse grid intervals containing high noise levels (EPA 2013). Also, measurements will be made at 10-foot intervals through the first 50 feet above the injection interval and at 20-foot intervals within 100 feet above that zone, and at 20-foot intervals within the base of the lowermost USDW.

Interpretation of noise logs requires establishment of a baseline noise level, with departures from baseline noise levels indicating an anomaly potentially associated with loss of external mechanical integrity. The threshold noise level indicating an anomaly will be set following recommendations of the service provider and equipment manufacturer. Any failure in external MIT indicated by a noise log will be further confirmed using another approved external MIT method prior to taking measures to remedy the situation.

See Section E.I.1.4 of the QASP for detailed information on the noise logging tool and its measurement specifications (e.g., range, precision, spatial resolution).

E.5. Analysis of CO_2 Stream [40 CFR 146.90(a)]

CSS will analyze the CO_2 stream during the operation period to yield data representative of its chemical and physical characteristics and to meet the requirements of 40 CFR 146.90(a).

E.5.1. Sampling Location and Frequency

CSS will sample the CO_2 stream during the Injection period and test the samples via laboratory analyses. Table E.5-1 summarizes sampling location and frequency. Grab samples for laboratory analysis will be taken during the Injection period from the manual sample port at AE-3001, which is located immediately upstream the injection flow meter (FE-3001) and is in close proximity to Front Range 1-1, in conformance with the sample location requirements of 40 CFR 98.444(b)(3). Sampling and testing for chemical analysis will occur quarterly per the requirements of 40 CFR 146.90(a) and 40 CFR 98.444(b)(3). Sampling and testing for isotope analysis will occur once every five years. CSS will temporarily increase the frequency of grab sampling and testing via laboratory analysis when major modifications are made to the upstream facilities that would likely impact the composition of the CO_2 source, or if one or more new sources of CO_2 are introduced to the system. No sampling will occur during the Pre-Injection or PISC periods since the CO_2 stream is not available during these periods.

Table E.5-1. Summary of CO_2 Stream Sampling Location and Frequency

Parameter	Sampling Location	Project Period	Frequency
Chemical Composition	Immediately upstream of injection flow meter	Pre-Injection	Not Applicable
		Injection	Quarterly
		PISC	Not Applicable
Isotope Concentration	Immediately upstream of injection flow meter	Pre-Injection	Not Applicable
		Injection	Every 5 Years
		PISC	Not Applicable

The CO_2 stream is nearly pure CO_2 (> 99 vol %). The source is CO_2-rich fermentation off gases that have first been water washed to reduce traces of ethanol and other volatile organic compounds, then further purified in the CO_2 liquefaction unit. The CO_2 liquefaction unit has multiple adsorption beds to remove common raw gas contaminants (e.g., water, hydrogen sulfide (H_2S) and other sulfur compounds) plus low-temperature distillation to remove non-condensable gases (e.g., hydrogen, nitrogen, oxygen, argon). Table E.5-2 is the International Society of Beverage Technologies (ISBT) guideline for beverage grade CO_2 composition. The CO_2 injectate stream is expected to meet (or exceed) this guideline even though the stream is not being sold for beverage applications.

Table E.5-2. Chemical Composition of CO_2 Injectate Stream

Bulk Constituents		
Component	**Value**	
	Minimum	**Typical**
Carbon Dioxide	99 vol %	99.99 vol %
Trace Constituents		
Component	**Value**	
	Maximum	**Typical**
Water	30 lb/MMSCF	12 lb/MMSCF
Oxygen	10 ppmw	10 ppmw
Hydrogen Sulfide	20 ppmv	0.47 ppmv
Total Sulfur	35 ppmv	0.11 ppmv

lb/MMSCF = pounds per million standard cubic feet
ppmw = parts per million, weight
ppmv = parts per million, volume
vol % = percent volume

CSS will also obtain isotope data for CO_2 stream during the Injection period. These data will be used for any investigations during the Injection and PISC periods of the project in the event that elevated concentrations of CO_2 are found in soil gas monitoring samples. The analytes and test methods used for isotope analysis of the CO_2 stream duplicate those for the soil gas monitoring samples.

E.5.2. Analytical Parameters

CSS will analyze the CO_2 for the constituents identified in Table E.5-3 using the methods listed.

Table E.5-3. Summary of Analytical Parameters for CO_2 Stream

Analyte	Analytical Methods(1)
Carbon Dioxide	ASTM D1946, ASTM D1945, GPA 2261, GPA 2177, ASTM E1747, EPA Method 3/3C, ISBT 2.0, or similar
Isotopes: $\delta^{13}C$ of DIC	Isotope ratio mass spectrometry(2)

Note 1: An equivalent method may be employed with the prior approval of the Underground Injection Control (UIC) Program Director
Note 2: Gas evaluation technique by Atekwana and Krishnamurthy 1998, with modifications made by Hackley et al. 2007
ASTM = ASTM International
$\delta^{13}C$ of DIC = ratio of two stable carbon isotopes in dissolved inorganic carbon

E.5.2.1. Sampling Methods

Representative samples will be taken at the designated sample station using materials, equipment, and procedures given in Section E.I.2.2.a/b of the QASP.

E.5.2.2. Laboratory to be Used/Chain of Custody and Analysis Procedures

Sample analysis will be conducted in-house by CSS (or its parent company Front Range Energy, LCC) or by a qualified outside laboratory using procedures described in Sections E.I.2.3 and E.I.2.4 in the QASP.

E.6. Monitoring of Operational Parameters [40 CFR 146.88(e)(1), 146.89(b) and 146.90(b)]

CSS will install and use continuous recording devices to monitor injection pressure, rate, and volume; the pressure on the annulus between the tubing and the long string casing; the annulus fluid volume added; and the temperature of the CO_2 stream, as required per 40 CFR 146.88(e)(1), 146.89(b), and 146.90(b).

E.6.1. Monitoring Location and Frequency

CSS will perform the activities identified in Table E.6-1 to monitor operational parameters and verify internal mechanical integrity of the injection well. All monitoring will take place at the locations and frequencies described in the table. Section A.II.2.2.2 of Well Construction Details contains a schematic of above ground equipment and instruments for Front Range 1-1.

Table E.6-1. Sampling Devices, Locations, and Frequencies for Continuous Monitoring of Front Range 1-1

Parameter	Device(s)	Location	Active Operation, Min Frequency	
			Sampling	Recording
CO_2 Pressure	PIT-3001	Surface – Immediately downstream of injection flow meter	2 seconds	1 minute
CO_2 Pressure	PI-3011	Surface – Wellhead Tubing	2 seconds	1 minute
CO_2 Pressure	PT-1101	Downhole – Proximate to packer	2 seconds	1 minute
CO_2 Temperature	TE-3001	Surface – Immediately downstream of injection flow meter	2 seconds	1 minute
CO_2 Temperature	TI-3010	Surface – Wellhead Temperature	2 seconds	1 minute
CO_2 Temperature	PT-1101	Downhole – Proximate to packer	2 seconds	1 minute
CO_2 Mass Flow Rate	FE-3001	Surface – From injection flow meter	2 seconds	1 minute
CO_2 Density	FE-3001	Surface – From injection flow meter	2 seconds	1 minute
Annular Pressure	PI-3012	Surface – Wellhead Annulus	2 seconds	1 minute
Annulus Fluid Volume	PI-3017	Surface – Annulus Fluid Tank Level	2 seconds	1 minute

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 gets recorded to digital format (such as a computer hard drive). For example, the data from the injection pressure transducer might be recorded to a hard drive once every minute.

E.6.2. Monitoring Details

Section E.2.7 of the QASP provides details on the operational instruments (e.g., calibration standards, precisions, and tolerances) and supporting information on the measurements and calculations.

CO_2 amounts can be measured and reported on either a mass or volumetric basis. In general, CO_2 amounts will be reported in this project on a mass basis using the unit of metric tons. Reported CO_2 amounts are from instantaneous or cumulative measurements made by the injection flow meter, which is a Coriolis meter that directly measures mass flow rates. Metric ton is the preferred unit as it is most widely used for regulatory reporting (e.g., quarterly cumulative mass flow is typically reported in metric ton).

CO_2 amounts will occasionally be reported on a volumetric basis. Unless otherwise stated, CO_2 volumes will be reported as standard volumes in barrels (bbl) referenced to the standard density of pure CO_2 at saturation pressure and 60°F since this convention is widely used in the United States (US) oil & gas and related industries. To be clear, standard volumes are not the same as actual volumes since density depends upon pressure, temperature, and composition.

Below is a sample calculation illustrating the conversion of 360 metric tons per day of CO_2 into barrels per day (bpd):

$$\left(\frac{360\ metric\ ton}{1\ day}\right)\left(\frac{2204.62\ lb}{1\ metric\ ton}\right)\left(\frac{1\ lbmol}{44.0095\ lb}\right)\left(\frac{6.4598\ gal}{1\ lbmol}\right)\left(\frac{1\ bbl}{42\ gal}\right)$$

$$= 2{,}770\ bpd$$

gal = gallon(s)
lb = pound(s)
lbmol = pound-mole(s)

with the conversion factors, molecular weight of CO_2, and standard density of CO_2 all sourced from the Gas Processors Suppliers Association (GPSA) Engineering Data Book (GPSA 2016).

Pressure (P) can be reported as either absolute pressure ($P_{absolute}$) or gauge pressure (P_{gauge}), where the relationship between the two is:

$$P_{absolute} = P_{gauge} + P_{atmospheric}$$

Pressure will generally be reported in this project using US customary units of psia for absolute pressure, psig for gauge pressure, and psi for differential pressure. It is customary in the US oil and gas industry to report pressure in the unit psi (without distinguishing the absolute, gauge, or differential reference point), which is often meant to be a gauge pressure - psig. Because the carbon capture and sequestration industry draws heavily from the oil and gas industry, this project will occasionally report gauge pressures in psi; whether this is a gauge pressure or a differential pressure can be usually be determined from context.

The reference value for atmospheric pressure ($P_{atmospheric}$) used to interconvert between absolute and gauge scales varies depending upon context. Standard barometric pressure at sea level is 14.696 psia, which is the reference value used for some pressure gauges (e.g., strain gauges) and certain engineering calculations (e.g., internal calculations for commercial software packages). Other physical gauges (e.g., Bourdon tube gauges) utilize the actual atmospheric pressure at the gauge location, which can often be approximated as the standard barometric pressure adjusted to the surface elevation of Front Range 1-1 per the barometric formula (Wikipedia 2023):

$$P_{atmospheric} \approx P_b \left[\frac{T_b + (h - h_b)L_b}{T_b}\right]^{\frac{-g_0 M}{R^* L_b}}$$

$$P_{atmospheric} \approx 14.696 \left[\frac{288.15 + (4752 - 0)(-0.0019812)}{288.15}\right]^{\frac{-(32.17405)(28.9644)}{(8.9494596\ x\ 10^4)(-0.0019812)}}$$

$$P_{atmospheric} \approx 12.3\ psia$$

where:

P_b	= reference pressure: 14.696 psia
T_b	= reference temperature: 288.15 Kelvin (K)
L_b	= temperature lapse rate: -0.0019812 K/ft
h	= height: 4,752 ft (ground level for Front Range 1-1 per stratigraphic well permit)
h_b	= reference height: 0 ft
R^*	= Universal gas constant: 8.9494596 x 10^4 lb ft^2/(lbmol K s^2)
g_0	= Gravitational acceleration: 32.17405 ft/s^2
M	= Molar mass of Earth's air: 28.9644 lb/lbmol

In some instances, it is necessary to adjust pressure values for hydrostatic head. The formula below provides an approximate relationship between pressure at the fracture pressure reference depth at Front Range 1-1 (bottom of Lyons Sandstone, depth: 8,958 feet total vertical depth [ft TVD]) and Front Range 1-1 bottom hole pressure as reported by PT-1101 for monitoring downhole pressure during the Injection and PISC periods (depth: 8,770 ft TVD):

$$\begin{aligned} P_{Fracture\ Pressure\ Reference\ Depth}, psig &\approx P_{PT-1101}, psig - \frac{\rho}{144}\frac{g}{g_c}\Delta h \\ &\approx P_{PT-1101}, psig - \frac{48}{144}(8{,}770 - 8{,}958) \\ &= P_{PT-1101}, psig + 63 \end{aligned}$$

The approximation is derived from hydrostatic head calculations under the following simplifying assumptions: a) Negligible frictional pressure loss in the injection system below the PT-1101 downhole pressure gauge, and b) fluid density (ρ) is constant at 48 pounds per cubic feet (lb/ft^3), which approximates the mass density of a CO_2: native formation fluid mixture at the pressure, temperature, and composition range of interest during the Injection and Post-Injection periods.

E.7. Corrosion Monitoring [40 CFR 146.90(c)]

To meet the requirements of 40 CFR 146.90(c), CSS will monitor well materials during the operation period for loss of mass, thickness, cracking, pitting, and other signs of corrosion to ensure that well components meet the minimum standards for material strength and performance.

CSS will monitor corrosion using the corrosion coupon method and collect samples according to the description herein.

E.7.1. Monitoring Location and Frequency

Corrosion coupons will be mounted into inline holders inserted into the CO_2 stream pipeline near the surface location of Front Range 1-1. This location was selected since it is representative of the CO_2 conditions in contact with the injection well components, yet it is easily accessible to CSS staff and subcontractors and is within the security perimeter for the surface equipment. On a quarterly basis during the Injection period, each coupon will be exposed to the CO_2 injectate, removed for cleaning and analysis, and replaced with a new coupon of the same material for the next testing cycle. No coupon testing will occur during the Pre-Injection or PISC periods since the CO_2 stream will not be available.

Table E.7-1. Well Component Materials and Coupons Crosswalk

	Well Component	Representative Coupons for Wetted Surfaces: Carbon Steel, API 5L X52 PSL2	Austenitic Stainless Steel, 304L SS - UNS S30403	Martensitic Stainless Steel, 13CR-L80 - UNS S42000	Superalloy Steel Alloy 925 - UNS N09925	Nickel-Plated Carbon Steel
Front Range 1-1	**Surface Facilities**					
	Wellhead	x				
	Surface Piping	x				
	Valves	x				
	Instruments		x			
	Subsurface					
	Casing - Long String			x		
	Packer				x	
	Tubing			x		
	Instruments					x

E.7.2. Sample Description

Table E.7-1 provides a crosswalk between the well component metallic surfaces expected to come in contact with CO_2 vs. corrosion coupons representing those wetted surfaces. The coupon types are identified by the type of steel, common name, and where appropriate the unified numbering system (UNS) identifier widely used in North America to designate alloy chemical composition or in some cases a specific mechanical or physical property. A UNS number alone does not provide a full material specification because it does not establish material properties, heat treatment, form, or physical property. The two left-most coupons listed in the heading of Table E.7-1 (i.e., Carbon Steel API 5L X52 PSL2 and Austenitic Stainless Steel 304L SS – UNS S30403) are commonly used materials in the upstream equipment and surface facilities for the injection well and thus are included in the testing matrix. The right-most coupons listed in Table E.7-1 are representative of the wetted metallic surfaces of subsurface well components as indicated by the "x". The coupons will be either commercially purchased corrosion coupons and/or coupons fabricated from excess materials used for construction and installation of the equipment.

E.7.3. Monitoring Details

Each new coupon will be prepared then installed into holders that place the coupon close to the center of flow for the full CO_2 stream, with flow passing the coupons any time injection is occurring except when the coupons are undergoing changeouts. No other processing equipment will act on the CO_2 stream past the placement of the coupon holders (other than piping, valving, and instruments); thus, the system will provide representative exposure of the coupons to the CO_2 composition, temperature, and pressures that will be seen at the wellhead and injection tubing.

CSS or its designated subcontractor will be responsible for initiating each monitoring event. Specifically, the CSS representative will:

- Coordinate preparation of new coupons for exposure to the CO_2 stream, following the method provided in Section E.I.2.2 of the QASP.
- Coordinate collection and installation of coupons with Operations. Retrieve previously installed coupons from their holders and install the newly prepared coupons for testing. No coupon previously exposed to the CO_2 stream is to be reused; only new prepared coupons will be installed per Section 2.1 of NACE International (NACE) SP-775-2018 (NACE 2018).
- Record all necessary identifying information during collection and installation of the coupons (e.g., field operator name & company affiliation, collection time and date, coupon location, coupon serial number)
- Visually inspect the retrieved coupons exposed to the CO_2 stream, and record written notes and photographs showing signs of erosion, pitting, scale, or other damage
- Place the retrieved coupons in protective packaging and ship them to the third-party analyst.
- Review and interpret test results, and report finding to US EPA.

See Section E.I.2.2 of the QASP for additional detail on the corrosion coupon program.

Complementary methods to corrosion coupon monitoring are the well integrity methods described earlier: Section E.3 Internal Mechanical Integrity, and Section E.4 and External Mechanical Integrity. These testing and monitoring plan elements ensure well integrity.

E.8. Pressure Fall-Off Testing [40 CFR 146.90(f)]

CSS will perform pressure fall-off tests during the injection period as described below to meet the requirements of 40 CFR 146.90(f).

E.8.1. Testing Location and Frequency

A pressure fall-off test will be performed in the injection well Front Range 1-1 at the following times:

- Prior to initiation of CO_2 injection
- At least once per every 5-year period during the Injection period
- At the end of the Injection period

E.8.2. Testing Details

Pressure fall-off tests are used to measure formation properties in the vicinity of the injection well. The objective of periodic testing is to monitor for any changes in the near-well bore environment that may impact injectivity and other well/reservoir performance metrics.

Pressure fall-off tests are conducted by ceasing injection for a period of time (i.e., shutting-in the well) and monitoring wellhead and bottomhole pressures and temperatures. The results of the pressure fall-off test depend in part on the injection conditions prior to shutting-in the well. Therefore, prior to the test, the injection rate and pressure will be kept as constant as practical and will be recorded by the instruments described previously in Section E.6 Monitoring of Operational Parameters.

The duration of the shut-in period will follow the US EPA guideline of three to five times the time required to reach infinite-acting radial flow (IARF) conditions (EPA 2013). This duration is well beyond the time period when wellbore storage effects can impact the data. Establishment of IARF conditions is indicated by a straight line on a standard semi-log plot of pressure response vs. log of the fall-off/recovery time.

Test results will be analyzed as follows:

- Linear-linear plots (aka Cartesian plots) of bottom-hole pressure versus time and bottom-hole temperature versus time for the period prior to shut-in and the duration of the test will be used to confirm stabilization prior to commencement of the test.
- Log-log plots of the pressure versus the time function and/or the semi-log derivative of pressure versus the time function will be used to identify flow regimes present in the well test. The appropriate time function used in these plots will be determined using the procedure discussed in Figure E.2-2 of the US EPA Region 6 Pressure Falloff Testing Guideline (EPA 2002a) and related US EPA documents (EPA 2002b, EPA 2003).
- Semi-log plot of pressure versus the log of the time function will be used to compute reservoir transmissibility, skin factor, radius of investigation, effective wellbore radius, reservoir injection pressure corrected, and other parameters as discussed in Figure E.2-2 of the US EPA Region 6 Pressure Falloff Testing Guideline (EPA 2002a) and related US EPA documents (EPA 2002b, EPA 2003). Any computer software used for curve matching of the data will be identified in the test report.

Common sense checks for anomalous data responses will be evaluated and explained as discussed in Figure E.2-2 of the US EPA Region 6 Pressure Falloff Testing Guideline (EPA 2002a) and related US EPA documents (EPA 2002b, EPA 2003). These checks include examinations for multiple fluid phases, gravity driven flow, and dissolution of CO_2 in brine.

The instruments used for the pressure fall-off test will be the same as those described previously in Section E.6 Monitoring of Operational Parameters.

E.9. Groundwater Quality and Geochemical Monitoring [40 CFR 146.90(d), 40 CFR 146.95(f)(3)(i)]

CSS will monitor groundwater quality for potential geochemical changes above the upper primary confining zone during the operation period to meet the requirements of 40 CFR 146.90(d). CSS will also monitor groundwater quality and geochemical changes in the first USDWs immediately above and below the injection zone (i.e., Entrada and Ingleside, respectively) per the requirements of 40 CFR 146.95(f)(3)(i).

E.9.1. Monitoring Locations and Frequency

CSS has installed a network of six stations (MS-1 through MS-6) for monitoring groundwater in the water table and the Upper Pierre aquifer (commonly used USDW) within and in the vicinity of the AoR and MMA as illustrated in Figure E.9-1. Each monitoring station contains a shallow groundwater monitoring well (SMW-1 through SMW-6) for monitoring groundwater within the surficial groundwater zone (water table). Three monitoring stations, MS-1 through MS-3, include a deeper monitoring well (DMW-1 through DMW-3) screened in the Upper Pierre Aquifer. See Attachment A.II Well Construction Details for depth and other details for each above confining zone monitoring well.

[redacted]

Groundwater quality at these monitoring stations will be continuously monitored for water level (pressure), temperature, conductivity, and salinity using downhole multi-parameter data loggers installed in each above confining zone monitoring well. Groundwater quality data are transmitted to CSS (and its subcontractors) by telemetry for real-time remote monitoring. Data loggers are also installed at each monitoring station for redundancy in case of a failure in the telemetry system. Geochemical monitoring and selected isotope analysis of groundwater above the upper primary confining zone will be accomplished by laboratory analysis of grab samples from each of the shallow and deep monitoring wells.

In addition, CSS will also monitor groundwater in the first USDW above the injection zone (i.e., Entrada Sandstone) and in the first potential USDW below the injection zone (i.e., Ingleside) via geochemical laboratory analyses of swab cup samples periodically taken from Front Range 2-1.

Table E.9-1 summarizes the planned monitoring methods, locations, and frequencies for groundwater quality and geochemical monitoring.

Table E.9-1. Summary of Above Upper Confining Zone Groundwater Quality and Geochemical Monitoring

Target Formations	Monitoring Activity	Monitoring Locations	Spatial Coverage	Project Period	Frequency
Alluvial aquifer (water table aquifer), Upper Pierre (Commonly used USDW)	Groundwater Quality	SMW-1, DMW-1 SMW-2, DMW-2 SMW-3, DMW-3 SMW-4 SMW-5 SMW-6	Grid of single point measurements within the AoR/MMA and vicinity	Pre-Injection	Continuous
				Injection	Continuous
				PISC	Initial: Continuous Maintenance: Data Loggers Only
Alluvial aquifer (water table aquifer), Upper Pierre (Commonly used USDW)	Geochemical Monitoring	SMW-1, DMW-1 SMW-2, DMW-2 SMW-3, DMW-3 SMW-4 SMW-5 SMW-6	Grid of single point measurements within the AoR/MMA and vicinity	Pre-Injection	Quarterly
				Injection	Year 1-2: Quarterly Year 3-5: Semi-annually Remainder: Annual
				PISC	Initial: Annual Maintenance: Every 5 years
Entrada Sandstone (First USDW above injection zone), Ingleside (First potential USDW below injection zone)	Geochemical Monitoring	Front Range 2-1	Single point measurements	Pre-Injection	Quarterly
				Injection	Year 1-2: Quarterly Year 3-5: Semi-annually Remainder: Annual
				PISC	Initial: Annual Maintenance: Every 5 years

The locations of the monitoring stations MS-1 through MS-6 were selected to provide broad coverage across the areal extent of the AoR and the MMA, while the main technical siting criterion for Front Range 2-1 was a location within the areal extent of the AoR during the Injection period. Table E.9-2 computes the above primary confining zone monitoring well density defined by the number of above confining layer groundwater wells per square area of the area extent of the AoR, MMA, and for the overall project. The US EPA used the assumption of one above upper primary confining zone monitoring well per two square miles of AoR for the purpose of estimating national costs for the Class VI program (EPA 2010), equivalent to an above confining zone monitoring well density of 0.5 wells per square mile for the areal extent of the AoR. The calculations in Table E.9-2 show the well density for the GS project exceeds the well density used by the US EPA in its rule making, suggesting the project has an adequate number of above primary confining zone groundwater monitoring wells.

Table E.9-2. Above Confining Zone Monitoring Well Density

Region	Number of Monitoring Wells	Well Identifiers	Region Surface Area, mi^2	Well Density, $wells/mi^2$
Areal Extent of AoR	9	SMW-1, DMW-1, SMW-2, DMW-2, SMW-3, DMW-3, SMW-4, SMW-5, SMW-6	6.4	1.4
Overall Project: Areal Extent of AoR + MMA	10	SMW-1, DMW-1, SMW-2, DMW-2, SMW-3, DMW-3, SMW-4, SMW-5, SMW-6, Front Range 2-1	12.5	0.8

mi^2 = square mile(s)

The locations of monitoring stations MS-1 through MS-6 were selected to provide broad coverage across the areal extent of the GS site, and also more specifically providing coverage near known artificial penetrations of the confining zones within the AoR (e.g., MS-4 is located near the surface location of Front Range 1-1, MS-5 is located near the bottom location of Front Range 1-1, and MS-1 is located near Front Range 2-1).

E.9.2. Analytical Parameters

Table E.9-3 identifies the parameters to be monitored and the analytical methods CSS will use.

Internal consistency of the geochemical results for each sample will be validated using the charge balance and material balance per the procedures given in Section E.I.2.5.c of the QASP. Outlier data will be identified using the procedures given in Section E.I.2.5.c of the QASP. Statistical time-series analysis will be used to establish baseline values for groundwater quality and geochemical analysis using a minimum of four quarterly samples taken during Pre-Injection. Material deviations of data taken during Injection and/or PISC from baseline values may potentially indicate non-containment, although a thorough analysis of alternative causes for such anomalous data should be carried out before declaring a non-containment event. See Section

H.4.3 of the Emergency Remedial and Response plan for actions to be taken in the event of a Potential Brine or CO_2 Leakage to USDW or the Surface.

E.9.3. Sampling Methods

Sampling methods for samples collected from MS-1 through MS-6 and Front Range 2-1 are described in Section E.I.2.2 of the QASP.

E.9.4. Laboratory to be Used/Chain of Custody Procedures

Sample handling and custody are described in Section E.I.2.3 of the QASP. Laboratory analytical methods are described in Section E.I.2.4 and Appendix C of the QASP. Field quality control is described in Section E.I.2.5 of the QASP.

Table E.9-3. Summary of Analytical and Field Parameters for Groundwater Samples

Locations/Target Formations	Analytes	Analytical Methods[1,2]
MS-1 through MS-6/ Alluvial Aquifer (Water Table) Upper Pierre (Commonly used USDW)	Cations: Al, Ba, Mn, As, Cd, Cr, Cu, Pb, Sb, Se, and Tl	ICP-MS EPA Method 6020
	Cations: Ca, Fe, Mg, Na, Potassium, and Si	ICP EPA Method 6010B
	Anions: Br, Cl, F, NO_3, and SO_4	Ion Chromatography EPA Method 300.0
	Isotopes: $\delta^{13}C$ of DIC	Isotope ratio mass spectrometry[3]
	Total dissolved solids	SM 2540C
	Alkalinity, Total (as $CaCO_3$)	SM 2320B
	Alkalinity, Carbonate (as $CaCO_3$)	SM 2320B
	pH (field)	Field Meter
	Dissolved CO_2[4] (field)	Field Meter
	Dissolved Oxygen (field)	Field Meter
	Turbidity (field)	Field Meter
	Specific conductance (field)	Field Meter
	Temperature (field)	Field Meter
	Depth to water (field)	Field Meter
	Water pressure/depth, temperature, and conductivity/salinity (field)	See Continuous Monitoring of Groundwater Quality
Front Range 2-1 Entrada Sandstone (First Aquifer Above Primary Upper Confining Zone)	Same Analytes and Analytical Methods as MS-1 through MS-6 samples except: a) Pressure and temperature readings will be recorded from the downhole instruments installed in Front Range 2-1 (upper zone) b) No field reading will be recorded for conductivity/salinity	

Note 1: An equivalent method may be employed with prior approval of the US EPA UIC Program Director

Note 2: All chemical analyses will be performed by a certified laboratory under the Environmental Laboratory Approval Program protocols; field measurements will be recorded by a qualified professional

Note 3: Gas evaluation technique by Atekwana and Krishnamurthy 1998, with modifications made by Hackley et al. 2007

Note 4: Pro-Oceanus - Solu Blu CO_2 sensor is proposed for use to measure dissolved CO_2 levels in the groundwater in the field using a flow through cell during well sampling events.

Al = Aluminum
As = Arsenic
Ba = Barium
Br = Bromide
Ca = Calcium
$CaCO_3$ = Calcium carbonate
Cd = Cadmium
Cl = Chloride
Cr = Chromium
Cu = Copper
Fe = Iron
ICP = Inductively coupled plasma
ICP-MS = Inductively coupled plasma mass spectrometry
Mg = Magnesium
Mn = Manganese
Sb = Antimony
Se = Selenium
Si = Silicon
SM = Standard Method
SO_4 = Sulfate
Tl = Thallium

E.10. Plume Tracking [40 CFR 146.90(g)]

The plume and pressure front monitoring methods are designed as a complementary suite of methods, with results from one method providing a means to confirm results from another, thus creating a certain amount of redundancy in the event of failure for any one method in the suite. CSS will employ a combination of direct and indirect geophysical methods to track the extent of the carbon dioxide plume to meet the requirements of 40 CFR 146.90(g). The direct method consists of periodic grab sampling from the bottom zone of Front Range 2-1 with laboratory geochemical and isotope analyses of the injection zone fluid sample. The indirect geophysical method utilizes a novel time-lapse vertical seismic profile (VSP) system. Section E.11 describes the complementary pressure front monitoring methods.

E.10.1. Plume Monitoring Location and Frequency

Table E.10-1 summarizes the methods that CSS will use to monitor the position of the CO_2 plume, including the activities, locations, and frequencies CSS will employ.

Table E.10-1. Plume Monitoring Activities

Target Formation	Monitoring Activity	Monitoring Location	Spatial Coverage	Period	Frequency
DIRECT PLUME MONITORING					
Lyons	Laboratory geochemical and isotope analysis of formation fluid grab samples	Front Range 2-1 (middle zone)	Single Point Location	Pre-Injection	Once
				Injection	Year 1-4: Annual Year 5+: Quarterly until plume passed, then cease monitoring
				PISC	Not Applicable
INDIRECT PLUME MONITORING					
Lyons	Time-lapse VSP	MMA and Vicinity	MMA and Vicinity	Pre-Injection	Once (baseline)
				Injection	Every 5 years, plus once at end of period
				PISC	Every 5 years, plus once at end of period

E.10.1.1. Direct Plume Monitoring

The main objective of the direct plume monitoring program is to experimentally confirm the time of passage for the CO_2 plume at Front Range 2-1. The direct plume monitoring method utilizes grab sampling and laboratory analyses of injection zone fluid samples collected from the middle zone of Front Range 2-1, with Front Range 2-1 located between the anticipated perimeters of the Year 5 – Year 8 perimeter of CO_2 plume as predicted by the computational model.

The planned sampling frequency for direct plume monitoring changes over time in order to catch the passage of the plume. A baseline Pre-Injection sample will be taken followed by annual sampling through the end of Year 4 of the Injection period since the plume is not anticipated to arrive during these times. Sampling frequency is increased to quarterly starting in Year 5 to ensure catching passage of the plume.

Quarterly sampling for direct plume monitoring will continue until the data indicate the plume has completely passed Front Range 2-1, at which point CSS will seek approval from the US EPA UIC Program Director to cease direct plume monitoring activities since the main objective of the direct plume monitoring program will be complete. The US EPA UIC Program Director decision to approve cessation of direct plume monitoring activities will be informed by data CSS provides on direct plume monitoring plus additional data from the complementary suite of plume and pressure front monitoring methods and the computation model.

E.10.1.2. Indirect Plume Monitoring

CSS conducted an extensive evaluation of currently available indirect geophysical methods for monitoring the plume during the Injection and Post-Injection periods of the GS project, and based on site-specific conditions selected a novel vertical seismic profile system to track the plume using a series of time-lapse surveys – see Appendix E-1 for additional detail. These data will in turn be used to support AoR re-evaluations and updates to the computational model as required in 40 CFR 146.84(b)(2) and 40 CFR 146.84(c). The current schedule of AoR re-evaluations once every five years is reflected in the frequency of surveys listed in Table E.10-1.

E.10.2. Plume Monitoring Details

E.10.2.1. Direct Plume Monitoring

The parameters to be analyzed as part of fluid sampling in the injection zone and associated analytical methods are presented in Table E.10-2. The parameter list for injection zone formation fluid samples differs slightly from the parameters presented earlier in Section E.9.2 for groundwater samples because the injection zone samples are expected to have a slightly different sample matrix as the CO_2 and formation fluids sweep through the injection zone.

See Sections E.I.2.2, E.I.2.3, E.I.2.4 of the QASP for more details on sampling procedure, sample handling and custody, and laboratory analytical methods, respectively.

E.10.2.2. Indirect Plume Monitoring

See Appendix E-1.

Table E.10-2. Summary of Analytical and Field Parameters for Fluid Sampling in the Injection Zone

Target Formation	Analytes	Analytical Methods[1,2]
Lyons (Injection Zone)	Cations: Al, Sb, As, Ba, Be, B, Cd, Ca, Cr, Co, Cu, Fe, Pb, Li, Mg, Mn, Ni, potassium, Se, SiO_2, Si, Ag, Na, Sr, V, Zn	ICP EPA Method 6010
	Anions: Br, Cl, F, NO_3, nitrite, and SO_4	Ion Chromatography EPA Method 300.0
	Isotopes: $\delta^{13}C$ of DIC	Isotope ratio mass spectrometry[3]
	Ammonia, as N	EPA 350.1
	Sodium Adsorption Ratio (SAR)	EPA 6010
	Mercury	EPA 7470
	Phenol	EPA 8270
	Oil and grease	EPA 1664A
	Ferric and ferrous iron	SM 3500
	Total dissolved solids	SM 2540C
	Alkalinity, Total (as $CaCO_3$)	SM 2320B
	pH	SM 4500
	Total sulfide and sulfide as H_2S	SM 4500
	Total CO_2	SM 4500
	Cyanide	SM 4500
	Total organic carbon	SM 5310C

Note 1: An equivalent method may be employed with prior approval of the US EPA UIC Program Director

Note 2: All chemical analyses will be performed by a certified laboratory under the Environmental Laboratory Accreditation Program (ELAP) protocols; field measurements will be recorded by a qualified professional

Note 3: Gas evaluation technique by Atekwana and Krishnamurthy 1998, with modifications made by Hackley et al. 2007

Ag = Silver
B = Boron
Be = Beryllium
Co = Cobalt
F = Fluoride
Li = Lithium
N = Nitrogen
Na = Sodium
Ni = Nickel
NO_3 = Nitrate
Pb = Lead
SiO_2 = Silicon dioxide
Sr = Strontium
V = Vanadium
Zn = Zinc

E.11. Pressure Front Tracking [40 CFR 146.90(g)]

The plume and pressure front monitoring methods are designed as a complementary suite of methods, with results from one method providing a means to confirm results from another, thus creating a certain amount of redundancy in the event of failure for any one method in the suite. CSS will employ a direct method of monitoring downhole pressure gauges installed in Front Range 1-1 and Front Range 2-1 to meet the requirements of 40 CFR 146.90(g)(1).

E.11.1. Pressure Front Monitoring Location and Frequency

Table E.11-1 summarizes the methods that CSS will use to monitor the position of the pressure front, including the activities, locations, and frequencies CSS will employ.

Table E.11-1. Pressure Front Monitoring Activities

Target Formation	Monitoring Activity	Location	Spatial Coverage	Period	Frequency
Lyons (Injection Zone)	Monitor downhole pressure gauge	Front Range 1-1	Single Point Location	Pre-Injection	Continuous (upon installation)
				Injection	Continuous
				PISC	Initial: Continuous Maintenance: Data Logger Only
	Monitor downhole pressure gauge	Front Range 2-1 (middle zone)	Single Point Location	Pre-Injection	Continuous (upon installation)
				Injection	Continuous
				PISC	Initial: Continuous Maintenance: Data Logger Only

E.11.2. Pressure Front Monitoring Details

Downhole pressure gauges are installed in Front Range 1-1 and Front Range 2-1 to measure over time the reservoir pressure at the specified gauge locations. These instruments produce essentially continuous readings of reservoir pressures, which are recorded at same frequency specified in Section E.6.1 for recording of Continuous Monitoring of Operating Parameters, with a local data logging back-up to improve resiliency of the data collection and recording system. The resulting recorded data are plotted over time to indicate the advancement/retreat of the pressure front at the two locations during the Injection and PISC periods. The resulting data are also used to update the computational model via history matching between the field data and the computational model results.

See Section E.I.1.4 of the QASP for more detail.

E.12. Soil Gas Monitoring [Project-Specific Testing and Monitoring]

A preliminary review of common GS project risks and site-specific conditions by CSS identified the potential for CO_2 leakage to the surface as a scenario that may not be adequately addressed by the minimum testing and monitoring requirements of 40 CFR 146.90. CSS will implement a soil gas monitoring program to identify and quantify potential CO_2 leakage to the surface across the MMA as part of its risk mitigation strategy.

E.12.1. Monitoring Locations and Frequency

CSS has installed 6 monitoring stations (MS-1 through MS-6) within and in the vicinity of the AoR and MMA (Figure E.9-1). Each monitoring station contains CO_2 gas sensors for measuring CO_2 concentrations in the upper vadose zone at approximately 3-5 feet below ground surface. Additionally, a set of 16 soil collars were installed at each location to serve as monitoring points for dynamic closed chamber (CO_2 efflux) measurements at the surface. See Attachment A.II Well Construction Details for details on the soil gas monitoring wells.

Soil gas CO_2 concentrations will be continuously monitored by CO_2 sensors equipped with data loggers placed in the upper vadose zone. The data will be transmitted during pre-injection, injection, and initial PISC periods to CSS via real-time telemetry, accessed remotely. Data loggers are also installed at each station for redundancy in case of failure of the telemetry system. Soil gas grab samples from the sampling points in the vadose zones will be analyzed in a laboratory. Efflux measurements of CO_2 concentrations versus time will be measured using a field infrared gas analyzer.

Table E.12-1 shows the planned monitoring locations and frequencies for soil gas monitoring. As discussed in Section E.9, the monitoring station locations were selected to provide full coverage of the areal extent of the AoR and the MMA, tailored to the project site specifics.

Table E.12-1. Monitoring Locations and Frequencies for Soil Gas Monitoring

Monitoring Activity	Monitoring Locations	Spatial Coverage	Project Period	Frequency
Monitor soil gas CO_2 across a network of stations	SCSW-1 SCSW-2 SCSW-3 SCSW-4 SCSW-5 SCSW-6	Single point measurements within AoR/MMA and vicinity	Pre-Injection	Continuous[(1)]
			Injection	Continuous[(1)]
			PISC	Initial: Continuous[(1)] Maintenance: Continuous[(1)] (data logger only)
Laboratory Analysis of Samples from Network of Stations	SVP-1 SVP-2 SVP-3 SVP-4 SVP-5 SVP-6	Single point measurements within AoR/MMA and vicinity	Pre-Injection	Quarterly
			Injection	Year 1-2: Quarterly Year 3-5: Semi-annually Remainder: Annually
			PISC	Initial: Annually Maintenance: Every 5 years
CO_2 Efflux Measurements at Each Station	MS-1, MS-2, MS-3, MS-4, MS-5, MS-6	4x4 grid of single point measurements within AoR/MMA and vicinity	Pre-Injection	Quarterly
			Injection	Year 1-2: Quarterly Year 3-5: Semi-annually Remainder: Annually
			PISC	Initial: Annually Maintenance: Every 5 years

Note 1: Continuous is defined as measurements taken at 30-minute intervals, with a 6-hour averaged reading recorded

E.12.2. Analytical Parameters

Table E.12-2 lists the analytes and analytical methods used for laboratory analysis of soil gas grab samples from the upper and lower vadose zones.

Table E.12-2. Summary of Analytical Parameters for Soil Gas Grab Samples

Analyte	Analytical Method
Argon	ASTM D1945 modified or similar/equivalent
Oxygen	ASTM D1945 modified or similar/equivalent
Nitrogen	ASTM D1945 modified or similar/equivalent
Carbon Dioxide	ASTM D1945 modified or similar/equivalent
Methane	ASTM D1945 modified or similar/equivalent
δ^{13} C of CO_2	SRI 8610C
Methane - field	Field meter (Landtec - GM500 or equivalent) - dual wavelength infrared cell with reference channel
Carbon Dioxide - field	Field meter (Landtec - GM500 or equivalent) - dual wavelength infrared cell with reference channel
Oxygen - field	Field meter (Landtec - GM500 or equivalent) - internal electrochemical cell
Carbon Monoxide - field	Field meter (Landtec - GM500 or equivalent) - internal electrochemical cell
Hydrogen Sulfide - field	Field meter (Landtec - GM500 or equivalent) - internal electrochemical cell

E.12.3. Sampling Methods

Sampling methods and sample preservation will be performed as described in Section E.I.2.2 of the QASP.

E.12.4. Laboratory to be Used/Chain of Custody Procedures

Sample handling and custody are described in Section E.I.2.3 of the QASP. Laboratory analytical methods are described in Section E.I.2.4 and Appendix D of the QASP. Field quality control is described in Section E.I.2.5 of the QASP.

E.13. Surface Air Monitoring [Project-Specific Testing and Monitoring]

A preliminary review of common GS project risks and site-specific conditions by CSS identified the potential for CO_2 leakage to the surface as a scenario that may not be adequately addressed by the minimum testing and monitoring requirements of 40 CFR 146.90. CSS will implement a surface air monitoring program as part of its risk mitigation strategy.

E.13.1. Monitoring Locations and Frequency

Table E.13-1 shows the planned monitoring locations and frequencies for the surface air monitoring program.

Table E.13-1. Monitoring Locations and Frequencies for Surface Air Monitoring

Monitoring Activity	Monitoring Locations	Spatial Coverage	Project Period	Frequency
Surface Air Concentration of CO_2	Front Range 1-1, Front Range 2-1	Single Point Measurement at Wellhead	Pre-Injection	Not Applicable
			Injection	Continuous
			PISC	Initial: Continuous Maintenance: Continuous (data logger only)

E.13.2. Analytical parameters

Surface air concentrations of CO_2 (the analyte) will be monitored using a non-dispersive infra-red (NDIR) sensor installed in the air at the wellheads.

E.13.3. Sampling Methods

The CO_2 sensors installed at the wellheads continuously sample air at the sensor point.

E.14. Seismic Monitoring [Project-Specific Testing and Monitoring]

CSS will implement a seismic monitoring plan to identify seismic risks and use the results of the seismic monitoring program to guide the respond to seismic events as described in Section H.4.5 of the Emergency and Remedial Response Plan. The monitoring and response plans are both aligned with seismic action plan used by the State of Colorado for the regulation of Class II wells.

The United States Geological Survey (USGS) network will be continuously monitored during Injection for validated triggering events. A triggering event is defined as a seismic event of greater than 2.5 local magnitude (M_L) with epicenter within 2.5-miles of Front Range 1-1. A validated triggering event is a triggering event that has been validated by USGS staff and added to their seismic event database. The response to triggering and validated triggering events is defined in Section H.4.5 of the Emergency and Remedial Response Plan.

E.15. References

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Appendix E-1. Indirect Geophysical Monitoring Method

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