CLASS VI PRE-OPERATIONAL TESTING PROGRAM

40 CFR 146.87

TRILLIUM CARBON STORAGE COMPLEX (TCSC)

Facility Information

Facility Name: Trillium Carbon Storage Complex (TCSC)
TCSC-1, TCSC-2, TCSC-3, TCSC-4, TCSC-5

Facility Contact: Claimed as PBI
[redacted]

Facility Address: Claimed as PBI

Well Location: Claimed as PBI

Well Name	Latitude	Longitude
TCSC-1	Claimed as PBI	Claimed as PBI
TCSC-2	Claimed as PBI	Claimed as PBI
TCSC-3	Claimed as PBI	Claimed as PBI
TCSC-4	Claimed as PBI	Claimed as PBI
TCSC-5	Claimed as PBI	Claimed as PBI

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Abbreviations and Acronyms

^{13}C	Carbon-13 (Isotope of Carbon)
^{14}C	Carbon-14 (Isotope of Carbon)
2D	Two-Dimensional
^{2}H	Deuterium (Isotope of Hydrogen)
3D	Three-Dimensional
^{3}H	Tritium (Isotope of Hydrogen)
AoR	Area of Review
AP	Artificial Penetration
Ar	Argon
ASTM	American Society for Testing and Materials
AZM	Above-Zone Monitoring Well
CALI	Caliper
CBL	Cement Bond Log
CFR	Code of Federal Regulations
CO_2	Carbon Dioxide
Cr	Chromium
DIC	Dissolved Inorganic Carbon
DOE	Department of Energy
DTS	Distributed Temperature Sensing
ECS	Elemental Capture Spectroscopy
EPA	Environmental Protection Agency
FMI	Formation Microimager
ft	Feet
GR	Gamma Ray
He	Helium

ICP-AES	Inductively Coupled Plasma – Atomic Emission
ICP-MS	Inductively Coupled Plasma – Mass Spectrometry
ICP-OES	Inductively Coupled Plasma – Optical Emission
IZM	In-Zone Monitoring Well
Kr	Krypton
lb	Pound
LDW	Logging While Drilling
MD	Measured Depth
MDT	Modular Formation Dynamics Tester
MWD	Measurement While Drilling
Ne	Neon
NMR	Nuclear Magnetic Resonance
NPHI	Neutron Porosity
PEF	Photoelectric Factor
PNL	Pulsed Neutron Log
psi	Pounds per Square Inch
RDT	Reservoir Description Tool
RES	Resistivity
RHOB	Bulk Density
Rn	Radon
SM	Standard Methods
SP	Spontaneous Potential
TCSC	Trillium Carbon Storage Complex
Trillium	Trillium Piketon, LLC
TVDSS	True Vertical Depth Subsea
UIC	Underground Injection Control
USDW	Underground Source of Drinking Water
UV	Ultraviolet
Xe	Xenon
YPIP	Years Post-Injection Phase

5. PRE-OPERATIONAL TESTING PROGRAM

5.1. EXECUTIVE SUMMARY

This **Pre-Operational Testing Program** has been designed to obtain the physical and chemical characteristics of the Trillium Carbon Storage Complex (TCSC) confining and storage reservoir zones prior to CO_2 injection pursuant to 40 CFR 146.87. Pre-operational testing will demonstrate compliance with the injection well construction requirements under 40 CFR 146.86 and inform subsequent injection and post-injection phase testing and monitoring activities. This testing plan includes a combination of well logging and geophysical surveying, mechanical integrity testing, geologic coring, fluid sampling, formation testing, and hydrogeological testing. These methods will generate datasets to aid in determining and/or verifying the depth, thickness, porosity, permeability, mineralogy, and geochemical profiles of the caprocks (i.e., [redacted] and [redacted]) and storage reservoirs (i.e., [redacted] and [redacted]). Data will also be collected from the first permeable zone above the caprock (i.e., [redacted]) to establish a baseline description of the geology, geochemistry, and groundwater quality of the above confining zone, pursuant to 40 CFR 146.82(a)(6), to inform injection and post-injection phase above-zone monitoring required by 40 CFR 146.90(d); testing and monitoring of the first permeable zone is a preventative measure in place to protect underground sources of drinking water (USDW) as it will allow for early detection of any out of zone CO_2 and/or reservoir fluids prior to them reaching shallow groundwater sources in the unlikely event there is loss of containment from the storage complex.

13 wells are planned to be drilled across the TCSC site including five CO_2 injection wells (TCSC-1, TCSC-2, TCSC-3, TCSC-4, TCSC-5), three in-zone monitoring wells (TCSC_IZM-1, TCSC_IZM-2, TCSC_IZM-3), and five above-zone monitoring wells (TCSC_AZM-1, TCSC_AZM-2, TCSC_AZM-3, TCSC_AZM-4, TCSC_AZM-5). All five injection wells are planned to be located on one well pad. Injection wells TCSC-1 and TCSC-2 will be completed within the [redacted] whereas injection wells TCSC-3, TCSC-4, and TCSC-5 will be completed within the [redacted]. All in-zone monitoring wells will be dual-zone completed and will be capable of monitoring both the [redacted] and [redacted] storage reservoirs. The five above-zone monitor wells are proposed to be completed within the [redacted] (i.e., first permeable zone above the caprock). All TCSC injection and monitoring wells will be utilized to collect baseline data and to subsequently monitor the in- and above-zone formations during the injection phase. Additional details regarding the testing and monitoring of project monitoring wells can be found in the **Testing and Monitoring Plan**. **Table 5-1** summarizes all TCSC project wells whereas **Figure 5-1** displays their locations with respect to project elements. Please reference **Table 5-11** for a summary of all baseline testing and monitoring activities that will inform subsequent injection and post-injection phase testing and monitoring.

Trillium Piketon, LLC (Trillium) will provide the Environmental Protection Agency (EPA) Region 05 Underground Injection Control (UIC) Program Director with the opportunity to witness all logging and testing along with a schedule of the injection well logging and testing activities 30 days prior to their commencement. The UIC Program Director will be promptly notified of any updates to the testing and logging schedule upon finalization. Results of proposed testing activities discussed throughout this plan will be summarized in a report and submitted to the UIC Program Director.

Table 5-1. TCSC well summary.

Well Type	Well Acronym	Well Trajectory	Zone Formation	CCS System Zone	Estimated Depth[A] (ft TVDSS/MD)	Quantity
Above-Zone Monitoring	TCSC_AZM-1 TCSC_AZM-2 TCSC_AZM-3 TCSC_AZM-4 TCSC_AZM-5	Vertical	Claimed as PBI [redacted]	First Permeable Zone	Claimed as PBI [redacted] ft MD	5
In-Zone Monitoring	TCSC_IZM-1 TCSC_IZM-2 TCSC_IZM-3	Vertical	a) Claimed as PBI [redacted] b) Claimed as PBI [redacted]	Storage Reservoir	*TCSC_IZM-1*: a) Claimed as PBI [redacted] b) Claimed as PBI [redacted] *TCSC_IZM-2*: a) Claimed as PBI [redacted] b) Claimed as PBI [redacted] *TCSC_IZM-3*: a) Claimed as PBI [redacted] b) Claimed as PBI [redacted]	3
CO_2 Injection	TCSC-1 TCSC-2	Deviated	Claimed as PBI [redacted]	Storage Reservoir	Claimed as PBI [redacted]	2
	TCSC-3 TCSC-4 TCSC-5	Deviated	Claimed as PBI [redacted]	Storage Reservoir	Claimed as PBI [redacted]	3

[A]Estimated depth of the formation top.

Claimed as PBI [redacted]

Figure 5-1. Aerial view of TCSC displaying the location of all injection and monitoring wells relative to project elements. A) represents the laterals of TCSC-1 and TCSC-3. B) represents the laterals of TCSC-2 and TCSC-4. C) represents the lateral of TCSC-5. CO_2 plume and pressure front boundaries represent the combined maximum extent from both the Claimed as PBI **and** Claimed as PBI **storage reservoirs.**

5.2. PRE-INJECTION LOGGING, SAMPLING, AND TESTING

The following testing and characterization activities will be performed in TCSC injection wells (TCSC-(1-5)) upon drilling to comply with the injection well construction requirements under 40 CFR 146.86 and the pre-operational testing requirements under 40 CFR 146.87. TCSC-1 and TCSC-2 will be completed within the Claimed as P [redacted] while TCSC-3, TCSC-4, and TCSC-5 will be completed within the Claimed as PBI. All CO_2 injection wells will have deviated trajectories and lateral sections within the storage reservoirs. Additionally, a vertical stratigraphic hole will be drilled for TCSC-3 prior to completing its deviated section for formation testing purposes (e.g., select well logging, coring, fluid sampling, fracture pressure testing, pressure fall-off testing). For additional information on injection well construction, please reference the **Well Construction Plan**.

5.2.1. Deviation Checks

Deviation measurements, pursuant to 40 CFR 146.87(a)(1), will be conducted approximately every 300 ft during injection well construction to ensure vertical conduits for fluid movement, such as diverging holes, are not created while drilling. The frequency of deviation checks will be increased as needed based on drilling responses. Throughout the build and lateral sections of each injection well, measurement while drilling (MDW) and logging while drilling (LDW) tools will be utilized for monitoring well deviation to ensure each well's trajectory remains as close to the proposed deviation plan as possible.

5.2.2. Open-Hole Well Logging Program

Open-hole well logging will be performed during injection well construction and prior to setting casing. Open-hole well log data will be collected to determine *in-situ* physical, chemical, geologic, and geochemical information on the storage reservoir and confining zones. Well logging will be performed throughout the entirety of each CO_2 injection well; wireline logging tools will be utilized down to the build section whereas logging while drilling (LDW) tools will be utilized throughout the lower build and lateral sections (please reference **Figure 5-2** for a generalized schematic of a lateral well). Basic wireline logs (e.g., triple combo) will be run throughout the vertical sections of each injection well. Additionally, advanced wireline logs (e.g., formation microimager, nuclear magnetic resonance, elemental capture spectroscopy) will be run throughout the storage complex (i.e., [redacted] through [redacted]) in the vertical stratigraphic hole of TCSC-3. The TCSC-3 stratigraphic hole is the only well that will be logged with advanced tools as its vertical section is within 300 ft of the vertical sections of the other CO_2 injection wells. LDW triple combo logs will be run throughout the lateral sections of TCSC-(1-5).

The following bullet points provide a brief description of the open-hole logging tools to be utilized within TCSC-(1-5). **Table 5-2** provides an additional summary of the proposed logging program. A more detailed description of each specific tool, measurement theory, and analysis protocol can be found in Bateman 2012 [1].

- **Mud Log –** A continuous visual description of drill cuttings circulated to the surface. The analysis of drill cuttings and the subsequent mud log reveals the relative lithology of the formations drilled through in addition to any hydrocarbon shows. Physical sample sets of drill cuttings will be collected and cataloged every 30 ft in the formations above the confining zone and every 10 ft within the storage complex (i.e., caprock and storage reservoir).

- **Caliper (CALI) –** A tool which provides information on the shape, volume, and roughness (rugosity) of the borehole. Caliper logs can also be used to better understand the quality of the geophysical log data obtained (e.g., caliper logs indicate zones of washout where logging data may be erroneous and need correction). The caliper log will be utilized to estimate wellbore volumes and well log data quality.

- **Spontaneous Potential (SP) –** A logging tool which measures the natural electrical potential generated from variations in salinity between the wellbore and formation fluids. Spontaneous potential data will be used for subsurface correlations, salinity calculations, and to identify intervals of higher permeability relative to one another.

- **Gamma Ray (GR) –** A logging tool which measures the natural radioactivity of a geologic formation. Gamma ray log data will be used for subsurface correlations, depth shifting and matching of other test data, and to approximate clay and/or shale volumes.

- **Formation Bulk Density (RHOB) –** A logging tool which indirectly approximates the bulk density of a geologic formation. Bulk density data will be used in conjunction with other logging measurements to identify lithology and estimate the porosity (total and effective) of subsurface geologic formations.

- **Neutron Porosity (NPHI) –** A logging tool which indirectly approximates porosity by measuring the hydrogen content within a geologic formation (e.g., hydrogen within water and hydrocarbons). Neutron porosity data will be used in conjunction with other logging measurements to identify lithology and estimate the porosity (total and effective) of subsurface geologic formations.

- **Photoelectric Factor (PEF) –** A logging tool which measures photoelectric absorption. Because photoelectric absorption varies between elements, the tool's data yields information regarding basic lithology. Photoelectric factor data will be used to determine mineralogy and lithology of geologic formations.

- **Resistivity (RES) –** A logging tool that measures the electrical resistance of rocks (i.e., how easily a current travels through the rock). Resistivity data will be used to estimate and confirm salinity, fluid saturation, and porosity.

- **Formation Microimager (FMI)** – A tool which measures the electrical resistivity radially throughout the wellbore. Measurements from this tool are processed into images of the open wellbore that are colored by contrasting resistivity values. Formation microimager data will be used to identify any geologic bedding planes and associated contacts, natural and induced fractures (e.g., open, healed, induced), shows of porosity, and rock textures (e.g., sedimentary structures).

- **Acoustic Logs (Monopole and Dipole) –** A tool that measures the travel time of energy waves (i.e., compressional and shear) through geologic formations. Monopole acoustic logs measure the compressional wave travel time whereas dipole acoustic logs measure both compressional and shear wave travel times. Monopole acoustic logs will be used to characterize porosity, lithology, and generate synthetic seismograms for seismic well ties. Dipole acoustic logs will be used for geomechanical characterization (e.g., fracture and stress characterization).

- **Nuclear Magnetic Resonance (NMR) –** A logging tool that stimulates protons (i.e., causes hydrogen nuclei to spin) and measures their resulting magnetic signals; these signals can be processed to resolve information related to rock porosity and permeability, pore-body size, and fluid saturations independent of the rock matrix. Nuclear magnetic resonance data will be used to aid in calculating petrophysical properties (e.g., porosity, permeability, saturation) of the storage complex.

- **Elemental Capture Spectroscopy (ECS) –** A geochemical logging tool which estimates the elemental concentration of a rock. The tool uses neutron bombardment which results in atomic nuclei releasing characteristic gamma rays that can be captured and processed to determine the geochemical makeup of a geologic formation. Elemental capture spectroscopy data will be used to estimate petrophysical properties, fluid saturations, and volumetric proportions of minerals.

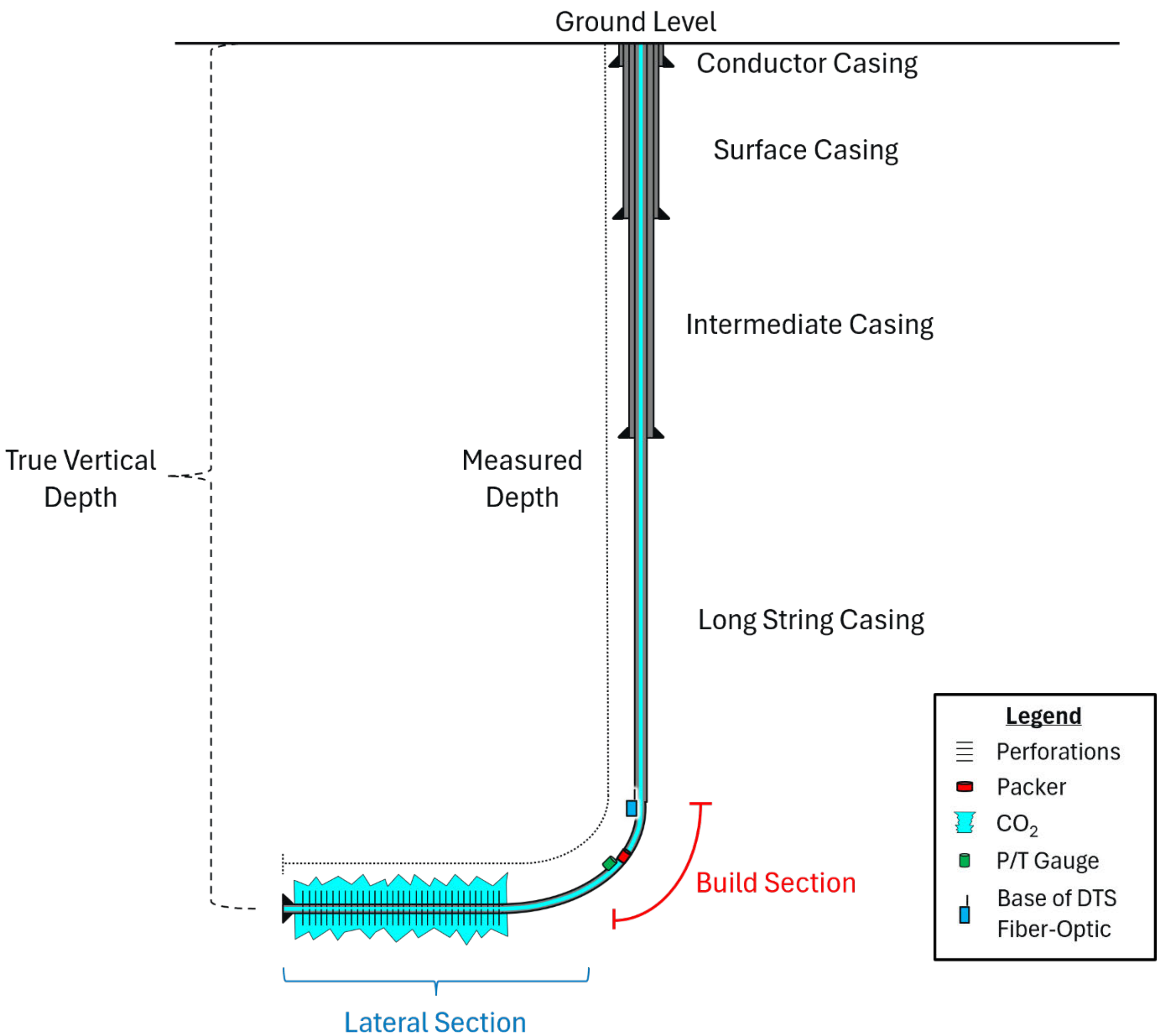

Figure 5-2. Generalized schematic of a lateral CO_2 injection well.

Table 5-2. Summary of the open-hole well logging program for TCSC injection wells.

Zone	Logging Activity	Purpose/Additional Comments
Surface Hole[A]		
Shallow Groundwater/USDW	Mud Log	Monitor drilling process and ensure safe drilling conditions Provide lithologic information while drilling to identify geologic formations penetrated
	Basic Wireline Logs: Caliper, Gamma Ray, Bulk Density, Neutron Porosity, Photoelectric Factor, Spontaneous Potential, Resistivity	Characterize geology Obtain baseline characteristic data from shallow formations
	Acoustic Monopole	Seismic well tie Acoustic porosity
Intermediate Hole[A]		
Above-Zone	Mud Log	Monitor drilling process and ensure safe drilling conditions Provide lithologic information while drilling to identify geologic formations penetrated
	Basic Wireline Logs: Caliper, Gamma Ray, Bulk Density, Neutron Porosity, Photoelectric Factor, Spontaneous Potential, Resistivity	Characterize geology and determine formation tops Obtain baseline characteristic data from above-zone formations
	Acoustic Monopole	Seismic well tie Acoustic porosity
Total Depth Hole[A]		
Storage Complex (i.e., caprock and storage reservoirs)	Mud Log	Monitor drilling process and ensure safe drilling conditions Provide lithologic information while drilling to identify geologic formations penetrated
	Basic Wireline Logs: Caliper, Gamma Ray, Bulk Density, Neutron Porosity, Photoelectric Factor, Spontaneous Potential, Resistivity	Characterize geology and determine formation tops Baseline formation evaluation
	Formation Microimager	Fracture characterization

Zone	Logging Activity	Purpose/Additional Comments
		Sedimentological and geological interpretation
	Acoustic Dipole	Seismic well tie Acoustic porosity Geomechanical analysis Fracture characterization
	Nuclear Magnetic Resonance	Baseline formation evaluation
	Elemental Capture Spectroscopy	Baseline mineral model Baseline formation evaluation

Note: For a brief description of logging tools, see section **5.2.2. Open-Hole Well Logging Program.**
[A]For specific depths of wellbore sections, please reference each injection well's **Well Construction Plan**.

5.2.3. Cased-Hole Well Logging Program

Cased-hole well logging will be performed in TCSC-(1-5) after casing is set in each well. Cased-hole well logs will provide data that will be used to evaluate injection well construction and critical baseline profiles of geologic units for future comparison. **Table 5-3** summarizes the cased-hole logging program for each wellbore section. The following cased-hole logging tools are planned to be utilized to characterize the subsurface and evaluate injection well construction pursuant to 40 CFR 146.87(2)(ii) and (3)(ii):

- **Ultrasonic Imaging Tool** – This logging tool measures acoustic impedance within cement which can be used to estimate well integrity and zonal isolation. Ultrasonic imaging tool data will be utilized to create maps of casing integrity and cement, identify solid (i.e., cement), liquid, or gas between the casing and formation, and identify corrosion or casing damage.

- **Cement Bond Log (CBL)** – CBL tools use acoustic waves to measure the integrity of a well's cement job. Acoustic transmitters and receivers measure signal attenuation to provide information on how well the casing and cement are bonded. CBLs provide an indication of cement-to-formation bond in the form of a variable density log which will be used to interpret the integrity of wellbore cement.

- **Pulsed Neutron Log (PNL)** – This tool uses neutron bombardment to measure the energy and capture of neutrons through the well's casing (also referred to as pulsed neutron capture). Pulsed neutron logs allow for the identification of mineralogy, lithology, fluid content, and saturations. Pulsed neutron data will be used to estimate brine and CO_2 saturations.

- **Temperature Log** – This tool measures temperature throughout a wellbore. Temperature logs will be utilized to collect a baseline temperature profile supportive of wellbore integrity assessments along with identifying zones taking out-of-zone brine and/or CO_2 by identifying temperature anomalies associated with leaks in casing and fluid movement along the wellbore.

- **Distributed Temperature Sensing (DTS) Fiber-Optics** – DTS fiber-optic cables continuously record temperature throughout a wellbore. Similar to standard temperature logging, DTS measurements can be used to assess wellbore integrity and zones taking fluid through the identification of temperature anomalies associated with leaks in casing and fluid movement along the wellbore. Analysis of DTS data will be the primary method for demonstrating external mechanical integrity.

Table 5-3. Summary of the cased-hole well logging program for TCSC injection wells.

Zone	Logging Activity	Purpose/Additional Comments
Surface Hole		
Shallow Groundwater/USDW	Cement Bond Log	Cement and external wellbore integrity
	Temperature Log	Cement and external wellbore integrity
Intermediate Hole		
Above-Zone	Cement Bond Log	Cement and external wellbore integrity
	Ultrasonic Imaging	Cement and external wellbore integrity
	Temperature Log	Cement and external wellbore integrity
Total Depth Hole		
Storage Complex (i.e., caprock and storage reservoirs)	Cement Bond Log	Cement and external wellbore integrity
	Ultrasonic Imaging	Cement and external wellbore integrity
	DTS Fiber-Optic	External wellbore integrity Baseline static temperature profile
	Pulsed Neutron Log	Baseline mineralogy/lithology Baseline fluid content Baseline fluid saturations

5.2.4. Mechanical Integrity Testing Program

Mechanical integrity testing will be performed in TCSC-(1-5) throughout the lifespan of TCSC. A well has mechanical integrity if:

- There is no internal leak in the casing, tubing, or packer (40 CFR 146.89(a)(1)).
- There is no significant external fluid movement into a USDW through channels adjacent to the injection wellbore (40 CFR 146.89(a)(2)).

Pursuant to 40 CFR 146.87(a)(2)(ii), 146.87(a)(3)(ii), and 146.87(a)(4), internal and external mechanical integrity will be demonstrated prior to injection operations. During injection well drilling and after casing is set and cemented, a casing pressure test along with cement bond, ultrasonic, and temperature logging will be performed. Upon injection well completion and prior to operations, internal and external mechanical integrity will be demonstrated with a standard annulus pressure test and DTS fiber-optic measurements, respectively. A summary of the internal and external mechanical integrity tests to be performed are displayed in **Table 5-4**.

5.2.4.1. Internal Mechanical Integrity

Prior to injection operations, internal mechanical integrity will be demonstrated in TCSC-(1-5) with a standard annulus pressure test pursuant to 40 CFR 146.87(a)(4)(i); this test will include pressurizing the annulus to a specified level and observing its pressure for an established period of time [2]. A loss of internal mechanical integrity can then be detected by a significant change in pressure which indicates the annular space is not sealed and is communicating with the tubing.

Table 5-4. Summary of TCSC injection well mechanical integrity testing.

Mechanical Integrity Test Type	Testing Method	Tested Interval	Test Frequency
Internal	Annulus Pressure Test	Long string/tubing	Once after well completion and prior to injection operations
External	Casing Pressure Test	Each casing section (i.e., surface, intermediate, long string)	After casing installation and prior to drilling each wellbore section
External	Cement Bond, Ultrasonic, and Temperature Log	Each casing section (i.e., surface, intermediate, long string)	After casing installation
External	DTS fiber-optic measurements	Long string	Once after well completion and prior to injection operations

The initial annulus test parameters will include pressurizing the annulus to 1,000 psi in the injection well for a 30-minute time period while a pressure differential of 200 psi will be kept between the annulus and tubing. The annulus and tubing pressures will be monitored and recorded every five minutes. Once the 30-minute test period ends, final pressures will be recorded to determine if there has been a significant pressure change. If a change in pressure of 10% or more is detected, the well will have failed the internal mechanical integrity demonstration. A description of the test to be performed and the opportunity to witness the test will be provided to EPA Region 05 at least 30 days in advance of the internal mechanical integrity test pursuant to 40 CFR 146.87(f). Trillium will report the results of the initial annulus pressure test to the UIC Program Director within 30 days of testing pursuant to 40 CFR 146.91(b).

The annulus pressure test described has been designed following EPA UIC No. 39 guidance "Pressure testing injection wells for Part 1 (Internal) Mechanical Integrity" [3]. Following the initial anulus pressure test, injection pressure, rate, and volume along with annulus pressure and volume will be continuously monitored throughout the injection phase to demonstrate internal mechanical integrity pursuant to 40 CFR 146.88(d), 146.89(a)(1), and 146.89(b). For further details on mechanical integrity demonstrations throughout the injection phase, please reference section **7.3 Mechanical Integrity Testing** of the **Testing and Monitoring Plan**.

5.2.4.2. External Mechanical Integrity

Prior to injection operations, external mechanical integrity will be demonstrated through the interpretation and reporting of DTS fiber-optic measurements pursuant to 40 CFR 146.87(a)(4)(iii). DTS fiber-optic cables deployed in each injection well (TCSC-(1-5)) will continuously measure temperature from at least the base of the caprock to the surface. Similar to standard temperature logging, DTS measurements will be used to identify leaks in casing based on the principle that fluid leaking from the wellbore will produce temperature anomalies. However, DTS fiber-optic cables provide various advantages over standard temperature logging such as reliability in hostile environments and high spatial, time, and temperature resolution [4]. Should DTS measurements not be available or adequate for demonstrating external mechanical integrity, pulsed neutron logs (i.e., oxygen activation log) and/or standard temperature logs will be utilized for external mechanical integrity demonstrations pursuant to 40 CFR 146.87(a)(4)(ii) and (iii), respectively.

While DTS fiber-optic cables will record temperature continuously, official external mechanical integrity demonstrations will involve shutting in the well to allow temperature to change toward static geothermal conditions [2]. Temperature profiles will then be analyzed for temperature anomalies indicative of leaks in casing and fluid movement along the wellbore. Baseline temperature profiles and a demonstration of external mechanical integrity will be collected and performed prior to injection operations pursuant to 40 CFR 146.87(a)(4)(iii). The results of baseline external mechanical integrity tests will be reported to the UIC Program Director within 30 days of testing pursuant to 40 CFR 146.91(b). For additional information on DTS fiber-optic measurements and mechanical integrity testing, please reference section **7.3 Mechanical Integrity Testing** of the **Testing and Monitoring Plan**.

5.2.5. Coring Program

Pursuant to 40 CFR 146.87(b), rock cores will be collected from all CO_2 injection wells in the form of whole and/or sidewall cores. Please reference **Table 5-5** for a summary of the whole core acquisition plan and **Table 5-6** for a summary of the whole core testing and analysis plan. To augment whole core sections, sidewall core may also be collected from intervals identified as those of interest (i.e., good confining zone and storage reservoir shows); **Table 5-7** summarizes this sidewall core acquisition and testing plan.

Approximately 300 ft of core will be collected from the TCSC-3 stratigraphic wellbore and approximately 60 ft of core will be collected from each CO_2 injection well during their respective drilling and construction operations. Core will be obtained from all formations of interest including:

1. Claimed as PBI (i.e., primary Claimed as PBI caprock)
2. Claimed as PBI (i.e., storage reservoir)
3. Claimed as PBI (i.e., Claimed as PBI caprock)
4. Claimed as PBI (i.e., storage reservoir)

Because the vertical section of each injection well is proposed to be within Claimed as PBI and Claimed as PBI cores will be collected from the TCSC-3 stratigraphic wellbore. Additionally, Claimed as PBI core will be collected in the laterals of TCSC-1 and TCSC-2 whereas Claimed as PBI core will be collected in the laterals of TCSC-3, TCSC-4, and TCSC-5.

Analytical tests planned to be performed on the cores collected include routine core analysis (i.e., porosity, permeability, grain density, lithology, fluid saturation), geologic and mineralogic analysis (i.e., core/thin section descriptions and x-ray diffraction), and special core analysis (i.e., geomechanics, geochemical compatibility testing, mercury intrusion capillary pressure, relative permeability, and threshold entry pressure).

Table 5-5. Summary of the whole core acquisition plan for TCSC injection wells.

Zone	Formation and Lithology	Estimated Depths[A] from Model (ft MD)	Anticipated Run Length (ft)	Location
Caprock	[redacted]	[redacted]	30 - 90	TCSC-3 stratigraphic hole
Storage Reservoir	[redacted]	[redacted]	30 – 90	TCSC-1 TCSC-2 TCSC-3 stratigraphic hole
Caprock	[redacted]	[redacted]	30 – 90	TCSC-3 stratigraphic hole
Storage Reservoir	[redacted]	[redacted]	30 – 90	TCSC-3 stratigraphic hole TCSC-3 TCSC-4 TCSC-5

[A]Estimated depths are ranges along wellbore trajectories that intervals of interest will be selected from and cored.

Table 5-6. Summary of the whole core testing and analysis plan for TCSC injection well core.

Testing Activity	Description	Zone
General Processing	Core slabbing and photography (UV/white light)	Caprocks (i.e., [redacted]e and [redacted]) and storage reservoirs (i.e., [redacted] and [redacted])
Routine Core Plug Analysis	Porosity, permeability, grain density, lithology, fluid saturation, fluorescence	
Geologic and Mineralogic Analysis	Thin section petrography X-ray diffraction Geological/sedimentological description	
Special Core Analysis	*Geomechanics:* triaxial compressive testing, triaxial ultrasonic testing, Brazil testing, pore volume compressibility Mercury intrusion capillary pressure Relative permeability Threshold entry pressure *Geochemical compatibility testing:* scaling tendencies, co-injection of CO_2/brine to assess effluent and rock mineralogy alterations	

Table 5-7. Summary of the sidewall core acquisition plan for TCSC injection wells.

Sample Selection	Zone	Analysis
The number and location of sidewall core intervals will be selected based on caprock and reservoir rock shows interpreted from well logs, formation tests, and mud logs	Caprocks (i.e., [redacted] and [redacted]) and storage reservoirs (i.e., [redacted] and [redacted])	Routine porosity, permeability, grain density, lithology, fluorescence

5.2.6. Fluid Sampling Program

Pursuant to 40 CFR 146.87(b), (c), and (d)(3), fluid samples from each storage reservoir (i.e., [redacted] and [redacted]) will be collected prior to injection operations. [redacted] and [redacted] fluid samples will be collected from the stratigraphic wellbore of TCSC-3. Fluid samples will be collected in open-hole conditions via wireline formation testers such as the modular formation dynamics tester (MDT), reservoir description tool (RDT), or equivalent. Fluid sampling methods will also collect information on reservoir pressures and static fluid levels. Reservoir fluid samples will be collected, stored, and transported using the protocols discussed in section **7A.2.4 Sample Handling and Custody** of the **Quality Assurance and Surveillance Plan**. Any fluids introduced into the wellbore environment throughout the drilling, conditioning, cementing, or testing process will be removed prior to fluid sampling to ensure representative samples of the subsurface system. The preliminary parameters and analytical methods for TCSC fluid samples are summarized in **Table 5-13**.

5.2.7. Formation and Fracture Pressure Testing

Pursuant to 40 CFR 146.87(c) and (d), *in-situ* reservoir pressure and fracture pressure will be determined for the storage reservoirs (i.e., [redacted] and [redacted]) and their respective confining zones (i.e., [redacted] and [redacted]). Wireline formation testers such as a MDT, RDT, or an equivalent tool will be utilized to perform wireline stress tests in each formation of interest. Stress tests will be performed in the open-hole wellbore of the TCSC-3 stratigraphic hole within the [redacted] and [redacted] to obtain *in-situ* reservoir and fracture pressure information on the confining zones pursuant to 40 CFR 146.87(d)(1). Additionally, stress tests will be performed within the [redacted] in TCSC-(1-2) and within the [redacted] in TCSC-(3-5) to obtain *in-situ* reservoir and fracture pressure information on the storage reservoirs pursuant to 40 CFR 146.87(d)(1).

Wireline stress testing involves a tool string with a packer arrangement, pump, and pressure gauges that locally press up against and isolate a several foot interval along the wellbore. The selected interval is then pressurized to obtain data that can be used to determine each formations fracture pressure pursuant to 40 CFR 146.87(d)(1). Wireline stress test measurements will also be used to verify, calibrate, and supplement well log-based estimates of fracture pressure determined by dipole acoustic logging. Should wireline stress testing tools not be available or adequate for collecting information needed for determining fracture pressure, step-rate testing will provide the required fracture pressure information. For a summary of the formation and fracture pressure testing program, please reference **Table 5-8**.

Table 5-8. Summary of the formation and fracture pressure testing to be performed in TCSC injection wells.

Parameter	Method	Formation	Location	Frequency
Formation and Fracture Pressure	Wireline Stress Test via Formation Testing Tool	a) Claimed as PBI [redacted] b) Claimed as PBI [redacted] c) Claimed as PBI [redacted] d) Claimed as PBI [redacted]	a) TCSC-3 stratigraphic hole b) TCSC-(1-2) c) TCSC-3 stratigraphic hole d) TCSC-(3-5)	Once during well construction

5.2.8. Hydrogeologic Testing Program

Upon injection well completion and prior to operation, pressure fall-off testing will be performed in the Claimed as P [redacted] and Claimed as PBI [redacted] storage reservoirs to verify their hydrogeologic characteristics pursuant to 40 CFR 146.87(e). Pressure fall-off tests are designed to measure reservoir properties, such as transmissivity, in the vicinity of the wellbore to verify large scale injectivity and to identify the presence of flow boundaries that could impact injectivity. Please reference **Table 5-9** for a summary of the hydrogeologic testing to be performed in each TCSC injection well.

Best practices for pressure fall-off testing will be followed such as those discussed in EPA Region 6 UIC Pressure Falloff Testing Guideline [5]. The pressure fall-off test will include a period of injection followed by a period of no injection or shut-in. Prior to the shut-in portion of the fall-off test, a constant injection rate will be maintained for a suitable amount of time in order to produce a measurable pressure transient. Following the injection period of the fall-off test, the injection well will be shut-in at the wellhead to reduce wellbore storage effects. The shut-in period of the fall-off test will last long enough for adequate pressure transient data to be collected and to calculate the average pressure.

Table 5-9. Summary of the hydrogeologic testing to be performed in TCSC injection wells.

Parameter	Method	Formation	Location	Frequency
Hydrogeologic Characteristics	Pressure fall-off test	a) Claimed as PBI [redacted] b) Claimed as PBI [redacted]	a) TCSC-(1-2) b) TCSC-(3-5)	Once during well construction

5.3. TESTING AND MONITORING BASELINE DATA

Prior to injection, various tests will be performed to collect baseline data that will be used to identify any significant changes in the injectate stream, wellbore integrity, corrosion, properties of the storage complex and/or above-zone, and CO_2 plume and pressure front migration. The following pre-injection testing and monitoring activities will provide baseline profiles that will inform subsequent injection and post-injection phase testing and monitoring:

- CO_2 stream analysis
- Internal and external mechanical integrity testing
- Corrosion monitoring
- Groundwater quality and geochemical monitoring
- Hydrogeologic testing
- Geophysical imaging
- Direct pressure front monitoring

For a summary of the baseline testing and monitoring methods, locations, and frequencies, please reference **Table 5-11**.

5.3.1. CO_2 Stream Analysis

Prior to injection, the contents of the CO_2 stream will be analyzed to a sufficient frequency to yield representative chemical and physical profile data pursuant to 40 CFR 146.82(a)(7)(iv). The analysis of the CO_2 injectate stream prior to injection is a critical element of the baseline testing and monitoring program; the analysis will provide the chemical and physical profiles of which the injectate stream will be monitored for at the surface and within each monitoring well throughout the subsequent injection phase. The CO_2 stream will be physically sampled downstream of the compression facilities and upstream of all injection wells. For a summary of the expected physical and chemical characteristics of the CO_2 stream, please reference **Table 5-10**. Please reference section **7.4.1 Carbon Dioxide Stream Analysis** of the **Testing and Monitoring Plan** for additional information on the proposed CO_2 stream and its respective testing and monitoring.

Table 5-10. Summary of the expected physical and chemical characteristics of the CO_2 injectate stream at TCSC.

Parameter[A]	Expected Value	Unit
Physical Characteristics		
Pressure[B]	[redacted]	psi
Temperature[C]	[redacted]	°F
Chemical Characteristics		
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]

[A]This list is subject to change based on source injectate stream composition results.

[B]Represents pressure at the CO_2 outlet. Injectate pressure will be adjusted accordingly to meet desired injection rate.

[C]Represents the temperature the injectate stream [redacted].

Table 5-11. Summary of the baseline testing and monitoring activities at TCSC.

Monitoring Category	Monitoring Parameter	Method or Equipment	Location	Baseline Phase Frequency (One Year Prior to Injection)	40 CFR Reference
CO_2 Stream Characterization	Chemical analysis	Physical sampling and laboratory analysis	Downstream of CO_2 compression facilities and upstream of TCSC-(1-5)	Once prior to injection	146.82(a)(7)(iv)
Mechanical Integrity Testing	Internal	Annulus pressure test	TCSC-(1-5)	Once prior to injection	146.87(a)(4)(i) 146.89(a)(1) 146.89(b)
	External	DTS fiber-optic or equivalent	TCSC-(1-5)	Once prior to injection	146.87(a)(4)(iii) 146.89(a)(2) 146.89(c)(2)
Corrosion Monitoring	Corrosion	Corrosion coupon(s)	Immediately upstream of TCSC-(1-5) on well pad	Once prior to injection	146.90(c)
Groundwater Quality and Geochemical Monitoring	Above-Zone (i.e., First Permeable Zone Above Caprock)	a) Fluid sampling and laboratory analysis b) Downhole pressure measurements	TCSC_AZM-(1-5)	(a) Quarterly (b) Continuous	146.82(a)(6) 146.90(d)
	In-Zone (i.e., Claimed as PBI [redacted] and Claimed as PBI [redacted])	Fluid sampling via wireline formation testers and laboratory analysis	TCSC-3 stratigraphic hole	Once during well construction	146.82(a)(6) 146.87(b) 146.87(c) 146.87(d)
Hydrogeologic Testing	Hydrogeologic characteristics of storage reservoirs	Pressure fall-off test	TCSC-(1-5)	Once prior to injection	146.87(e)(1)

Monitoring Category	Monitoring Parameter	Method or Equipment	Location	Baseline Phase Frequency (One Year Prior to Injection)	40 CFR Reference
Indirect CO_2 Plume Imaging	Geophysical imaging of the subsurface prior to injection	Surface seismic (2D or 3D) or equivalent	TCSC site	One survey prior to injection	146.90(g)(2)
		Pulsed neutron logging	TCSC_AZM-(1-5) TCSC_IZM-(1-3) TCSC-(1-5)	Once prior to injection	
Direct Pressure Front Monitoring	In-Zone (i.e., [redacted] and [redacted]) Pressures	Downhole pressure gauge(s)	TCSC_IZM-(1-3) TCSC-(1-5)	Continuous	146.90(g)(1)

5.3.2. Mechanical Integrity Testing

Pursuant to 40 CFR 146.87(a)(4), internal and external mechanical integrity will be demonstrated in all CO_2 injection wells prior to injection operations. Mechanical integrity testing (i.e., internal and external) is a key component of the baseline testing and monitoring program that ensures there are no significant leaks in the casing, tubing, or packer (i.e., internal mechanical integrity) or significant fluid movement throughout channels adjacent to the injection wellbore that could endanger USDWs (i.e., external mechanical integrity).

Prior to injection, internal mechanical integrity will be demonstrated with a standard annulus pressure test pursuant to 40 CFR 146.87(a)(4)(i). For additional information on the initial annulus pressure test, please reference section **5.2.4.1. Internal Mechanical Integrity**. Once the initial pressure test is performed in each injection well, internal mechanical integrity will be continuously monitored with an annulus monitoring system as described in section **7.4.3 Continuous Recording of Annulus Pressure and Fluid Volume** of the **Testing and Monitoring Plan**.

External mechanical integrity, prior to injection, will be demonstrated in all injection wells through the analysis of DTS fiber-optic measurements, or equivalent, pursuant to 40 CFR 146.87(a)(4)(iii). For additional information on DTS fiber-optic and external mechanical integrity, please reference section **5.2.4.2. External Mechanical Integrity** of this plan and section **7.3 Mechanical Integrity Testing** of the **Testing and Monitoring Plan**.

5.3.3. Corrosion Monitoring

Throughout the injection phase, well materials that are to be in contact with the CO_2 injectate will be monitored for corrosion such as loss of mass, thickness, cracking, pitting, and any other signs of corrosion pursuant to 40 CFR 146.90(c). Corrosion coupons of materials used in the construction of wells that are to be exposed to CO_2 will be sampled and analyzed (**Table 5-12**). Prior to injection operations, corrosion coupons will be photographed, visually inspected, dimensionally measured, and weighted for baseline values. Coupons will then be sampled and evaluated throughout the injection phase to ensure well components meet the minimum standards for material strength and performance pursuant to 40 CFR 146.86(b). For additional details on corrosion monitoring, please reference section **7.4.4 Corrosion Monitoring** of the **Testing and Monitoring Plan**.

Table 5-12. Summary of the materials to be monitored for corrosion at TCSC.

Equipment Coupon	Material of Construction	Location	Frequency
Long String Casing	[redacted], premium connection	Immediately upstream of TCSC-(1-5) on well pad	Once prior to injection
Injection Tubing	[redacted], premium connection		
Wellhead	Carbon, alloy, or stainless steel		
Packers	[redacted] VAM coupling		

5.3.4. Groundwater Quality and Geochemistry Analysis

Pursuant to 40 CFR 146.82(a)(6), groundwater quality and geochemical baseline measurements will be taken prior to injection. Samples will be obtained from the Claimed as PBI (i.e., anticipated first permeable zone above the caprock) in above-zone monitoring wells TCSC_AZM-(1-5). Fluid samples will be collected via well purging or an equivalent method [6] and sent to an approved laboratory for analysis. Samples are proposed to be collected quarterly throughout the year leading up to injection to account for any natural and/or seasonal variations. Additionally, fluid samples from the Claimed as PBI and Claimed as PBI storage reservoirs will be collected once during the construction of the TCSC-3 stratigraphic borehole. The analytes highlighted in **Table 5-13** will be tested for to create a baseline profile that can be used as a reference during injection and post-injection phase testing and monitoring; the parameters listed in **Table 5-13** will be used as water quality indicators and tracers to determine whether out of zone fluids have been introduced into the above-zone monitoring formation throughout the injection and post-injection phases. Baseline results will dictate parameter threshold values. Any parameters observed to be absent or non-significant to the project during baseline analysis will be removed from the testing and monitoring program; if baseline results indicate additional parameters to be monitored, they will be added to the program and analyzed in future events.

To supplement the geochemical fluid samples, downhole pressure measurements from the Claimed as PBI will be obtained via downhole gauges throughout the baseline phase. Downhole above-zone pressures will then be monitored throughout the injection and post-injection phases to identify any anomalous pressures potentially associated with unexpected out of zone CO_2 and/or reservoir fluids therefore acting as indirect water quality indicators.

Table 5-13. Summary of the analytical parameters and methods for baseline fluid samples at TCSC.

Parameters[A]	Analytical Methods[B]
Formation: Claimed as PBI [redacted] *[C]*	
Major Cations	ICP-AES, ICP-OES, ICP-MS, or equivalent *(EPA 6000 Series [7], EPA 200.7 [8], or equivalent)*
Major Anions	Ion Chromatography, Spectroscopy, or equivalent *(EPA 300.0 [9], EPA 300.1 [10], SM 4500 Series [11], or equivalent)*
Ammonia Nitrogen	Colorimetry, Titration, or equivalent *(EPA 350.1 [12], EPA 350.2 [13], or equivalent)*
Dissolved CO_2	Coulometric Titration, Gas Sensing Electrode, or equivalent *(ASTM D513-16 [14] or equivalent)*
Total Dissolved Solids	Gravimetry or equivalent *(EPA 160.1 [15], SM 2540C [16], ASTM D5907-18 [17], or equivalent)*
Alkalinity	pH Meter or equivalent *(SM 2320B [18], ASTM D3875-15 [19] or equivalent)*
pH	pH Meter or equivalent *(EPA 150.1 [20], SM4500H+B [21], ASTM D1293-18 [22], or equivalent)*
Temperature	Thermocouple or equivalent *(SM 2550B [23] or equivalent)*
Conductivity	Conductivity Meter or equivalent *(EPA 120.1 [24], SM 2510B [25], ASTM D1125-23 [26], or equivalent)*

Parameters[A]	Analytical Methods[B]
Formation: Peebles Dolomite, Rose Run Sandstone, Basal Sandstone[C]	
Density	Pycnometer, Hydrometer, Density Meter, or equivalent *(ASTM D1429-13 [27], ASTM D1480-21 [28], ASTM D4052-22 [29], or equivalent)*
Noble Gases: He, Ne, Ar, Kr, Xe, Rn[D]	Mass Spectrometry or equivalent
^{13}C of DIC and CO_2	Isotope Ratio Mass Spectrometry or equivalent
^{14}C of DIC and CO_2[D]	Accelerator Mass Spectrometry or equivalent
^{2}H of Water	Isotope Ratio Mass Spectrometry or equivalent
^{3}H of Water[D]	Accelerator Mass Spectrometry or equivalent

[A]Parameters may be added or subtracted to the sampling and analysis list depending on baseline results.
[B]Specific analytical methods will be selected in collaboration with the laboratory to perform the fluid testing and analysis to ensure parameters are appropriately analyzed. The methods and procedures selected will be provided to the Region 05 UIC Program Director.
[C]Both storage reservoirs (i.e., [redacted] and [redacted]) and the first permeable zone above the caprock (i.e., [redacted]) will be sampled prior to injection for baseline profiles. Only the first permeable zone will be sampled throughout the injection and post-injection phases.
[D]Noble gases, ^{14}C of DIC and CO_2, and ^{3}H of water will be analyzed in the first sampling event prior to injection. If parameters are not present or are non-significant to the project, they will be excluded from future sampling events.

5.3.5. Hydrogeologic Testing

Pursuant to 40 CFR 146.87(e)(1), the hydrogeologic characteristics of the [redacted] and [redacted] storage reservoirs will be tested in their respective injection wells prior to operations via an injectivity test such as a pressure fall-off test. Data from baseline pressure fall-off tests and those performed throughout the lifespan of TCSC will be used to better understand any reservoir changes throughout time and to ensure operational parameters are optimal for downhole conditions. For additional information on hydrogeologic testing, please reference section **5.2.8. Hydrogeologic Testing Program** of this plan and section **7.4.5 Pressure Fall-Off Testing** of the **Testing and Monitoring Plan**.

5.3.6. CO_2 Plume and Pressure Front Monitoring

As part of the **Testing and Monitoring Plan** and pursuant to 40 CFR 146.90(g), indirect and direct methods will be used to track CO_2 plume migration and pressure front propagation across the TCSC site, respectively.

Pursuant to 40 CFR 146.90(g)(2), repeat surface seismic (e.g., 2D or 3D) will be utilized to indirectly image the CO_2 plume across the TCSC site. Prior to injection operations, a 2D or 3D seismic survey will be collected as baseline data for the site; subsequent injection and post-injection phase seismic surveys will then be compared to the baseline survey to image the CO_2 plume and estimate its saturation throughout time. Prior to the seismic survey, feasibility studies such as fluid substitution modeling and seismic raytracing will be performed to ensure the best acquisition parameters to accurately image the plume across the TCSC site. In addition to the planned baseline seismic survey, pulsed neutron logging will be performed in all project wells (TCSC-(1-5), TCSC_IZM-(1-3), TCSC_AZM-(1-5)). Because baseline profiles will be collected in all project wells, pulsed neutron logging can be performed on an as needed basis throughout the lifespan of TCSC to (1) verify the presence and extent of the CO_2 plume within the storage reservoirs and/or (2) be used to detect and quantify any out of zone fluids in the above-zone in the unlikely event there is loss of containment from the storage complex. For additional information on CO_2 plume imaging, please reference section **7.6 Carbon Dioxide Plume and Pressure Front Tracking** of the **Testing and Monitoring Plan**.

Prior to injection and pursuant to 40 CFR 146.90(g)(1), baseline downhole pressure measurements will be recorded from the [redacted] and [redacted] storage reservoirs in all in-zone monitoring wells (TCSC_IZM-(1-3)) and CO_2 injection wells (TCSC-(1-5)) via downhole pressure gauges. Baseline pressure measurements can then be referenced throughout the injection and post-injection phases to track the elevated pressure front throughout the storage reservoirs over time. Additionally, in-zone pressure measurements will be used to inform operational parameters and verify and/or update the computational model to ensure TCSC is operating as permitted and that models are accurately predicting CO_2 plume and pressure front evolution. For additional information on direct pressure front tracking, please reference section **7.6 Carbon Dioxide Plume and Pressure Front Tracking** of the **Testing and Monitoring Plan**.

5.4. REFERENCES

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[9] *Determination of Inorganic Anions by Ion Chromatography*, EPA Method 300.0, rev. 2.1, 1993.

[10] *Determination of Inorganic Anions in Drinking Water by Ion Chromatography*, EPA Method 300.1, rev. 1.0, 1999.

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[21] *pH Value in Water by Potentiometry Using a Standard Hydrogen Electrode*, SM 4500H+B, 2011.

[22] *Standard Test Methods for pH of Water*, ASTM D1293-18, 2018.

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[25] *Conductivity – Laboratory Method*, SM 2510B, 2021.

[26] *Standard Test Methods for Electrical Conductivity and Resistivity of Water*, ASTM D1125-23, 2023.

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