CLASS VI INJECTION TESTING AND MONITORING PLAN

40 CFR 146.90

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 [redacted]

Well Location: Claimed as PBI [redacted]

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

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Abbreviations and Acronyms

°F	Degrees Fahrenheit
^{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)
4D	Four-Dimensional
AoR	Area of Review
AP	Artificial Penetration
Ar	Argon
ASTM	American Society for Testing and Materials
AZM	Above-Zone Monitoring Well
CFR	Code of Federal Regulations
CO_2	Carbon Dioxide
DCS	Distributed Control System
DIC	Dissolved Inorganic Carbon
DOE	Department of Energy
Dol	Dolomite
DTS	Distributed Temperature Sensing
EPA	Environmental Protection Agency
ERRP	Emergency and Remedial Response Plan
Fm	Formation
ft	Feet
Gr	Group
GS	Geologic Sequestration
He	Helium
ICP-AES	Inductively Coupled Plasma – Atomic Emission Spectrometry
ICP-MS	Inductively Coupled Plasma – Mass Spectrometry
ICP-OES	Inductively Coupled Plasma – Optical Emission Spectrometry
IZM	In-Zone Monitoring Well
Kr	Krypton
lb	Pound

Ls	Limestone
MD	Measured Depth
MIT	Mechanical Integrity Test
MMTpa	Million Metric Tons per Annum
NACE	National Association of Corrosion Engineers
Ne	Neon
P&ID	Process and Instrument Diagram
P/T	Pressure/Temperature
PISC	Post-Injection Site Care
PNL	Pulsed Neutron Log
psi	Pounds per Square Inch
QASP	Quality Assurance and Surveillance Plan
Rn	Radon
SCADA	Supervisory Control and Data Acquisition
Sh	Shale
SM	Standard Methods
Claimed as PBI [redacted]	[redacted]
Ss	Sandstone
TCSC	Trillium Carbon Storage Complex
Claimed as PBI [redacted]	[redacted]
Trillium	Trillium Piketon, LLC
TVDSS	True Vertical Depth Subsea
UIC	Underground Injection Control
USDW	Underground Source of Drinking Water
Xe	Xenon
YPIP	Years Post-Injection Phase

7. TESTING AND MONITORING PLAN

7.1. EXECUTIVE SUMMARY

This **Testing and Monitoring Plan** describes how Trillium Piketon, LLC (Trillium) will monitor the Trillium Carbon Storage Complex (TCSC) site, pursuant to 40 CFR 146.90, for the duration of the project's injection phase of 30 years. The **Testing and Monitoring Plan** has been designed to ensure that TCSC is operating as permitted and to ensure the injected carbon dioxide (CO_2) and/or storage reservoir fluids do not become a contamination risk to underground sources of drinking water (USDW). The plan includes:

- CO_2 stream analysis (40 CFR 146.90(a)).
- Continuous recording of operational parameters (40 CFR 146.90(b)).
- Corrosion monitoring (40 CFR 146.90(c)).
- Groundwater quality and geochemical monitoring above the confining zone (40 CFR 146.90(d)).
- Mechanical integrity testing (40 CFR 146.90(e)).
- Pressure fall-off testing (40 CFR 146.90(f)).
- CO_2 plume and pressure front tracking (40 CFR 146.90(g)).

13 wells are proposed 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 proposed to be located on one well pad. Injection wells TCSC-1 and TCSC-2 will be completed within the [redacted] (i.e., storage reservoir) whereas injection wells TCSC-3, TCSC-4, and TCSC-5 will be completed within the [redacted] (i.e., storage reservoir). Testing and monitoring activities including mechanical integrity testing, corrosion monitoring, pressure fall-off testing, and continuous recording of operational parameters (i.e., injection rate, volume, temperature, and pressure) will be performed in each CO_2 injection well or on their shared well pad. The three in-zone monitoring wells are proposed to be located along the modeled maximum extent of the CO_2 plume and within the area of review (AoR) to allow for direct pressure front tracking and CO_2 plume verification. In-zone monitoring wells are proposed to be dual-zone completed and will be capable of monitoring both the [redacted] and [redacted] storage reservoirs. The five above-zone monitoring wells are proposed to be completed within the [redacted] (i.e., first permeable zone above the caprock) and will be located in sensitive areas throughout the AoR such as near [redacted] and locations where groundwater is sourced from. Monitoring the first permeable zone above the caprock is a preventative measure in place that is best suited to detect any out of zone CO_2 and/or reservoir fluids prior to them reaching overlying USDWs in the unlikely event there is loss of containment from the storage complex.

This **Testing and Monitoring Plan** will be reviewed at a minimum of once every five years pursuant to 40 CFR 146.90(j). The plan will be adjusted accordingly to meet any changes to the facility or site conditions over time. All amended plans will be sent to the Region 05 Underground Injection Control (UIC) Program Director for approval as outlined in the permit modification requirements under 40 CFR 144.39 and 144.41. Results of activities described throughout this **Testing and Monitoring Plan** may trigger action according to the **Emergency and Remedial Response Plan** (**ERRP**).

7.2. OVERALL OBJECTIVES, APPROACH, AND CONCEPTUAL DESIGN FOR TESTING AND MONITORING

7.2.1. Plan Objectives and Approach

Trillium's **Testing and Monitoring Plan** has been designed to evaluate TCSC performance while ensuring the safety of local USDWs. The protection of USDWs, as required under the Environmental Protection Agency (EPA) UIC Class VI Rule (75 FR 77230), is the primary objective of the monitoring program at TCSC. Additionally, data collected throughout the duration of this plan will be used to demonstrate TCSC is operating as permitted, ensure the CO_2 plume and pressure front are moving throughout the storage reservoirs as predicted, and to validate and/or adjust the TCSC geological model. The monitoring data coupled with the geological model will support AoR reevaluations, a USDW non-endangerment demonstration, and guide post-injection site care (PISC) and site closure procedures required to meet the closure requirements of the UIC Class VI permit.

The **Testing and Monitoring Plan** will be reviewed at least once every five years pursuant to 40 CFR 146.90(j). Upon review, Trillium will submit an amended **Testing and Monitoring Plan** to the UIC Program Director or demonstrate that no amendment to the current plan is required. Results of the testing and monitoring activities described throughout this plan may trigger action according to the **Emergency and Remedial Response Plan**.

7.2.2. Testing and Monitoring Network Design

Trillium's testing and monitoring network consists of five CO_2 injection wells and eight monitoring wells (**Table 7-1**). The injection and monitoring wells have been strategically completed within various in- and above-zone formations to ensure TCSC is operating as permitted and for the protection of USDWs. Injection wells TCSC-1 and TCSC-2 will be completed within the Claimed as PBI whereas injection wells TCSC-3, TCSC-4, and TCSC-5 will be completed within the Claimed as PBI. Three in-zone monitoring wells are proposed to be dual-zone completed to monitor both the Claimed as PBI and Claimed as PBI storage reservoirs. Five above-zone monitoring wells are proposed to be completed within the Claimed as PBI (i.e., first permeable zone above the caprock) to detect any out of zone CO_2 and/or storage reservoir fluids prior to them reaching local USDWs in the unlikely event of loss of containment from the storage complex. **Figure 7-1** provides a generalized stratigraphic column for the site along with a schematic displaying the placement of each injection and monitoring well within individual formations (for official well schematics and additional information on injection well design, please reference the **Well Construction Plan**).

This **Testing and Monitoring Plan** describes the injection phase components of the testing and monitoring program (**Table 7-2**). For additional information on the testing and monitoring activities prior to and post-injection, please reference the **Pre-Operational Testing Program** and **Post-Injection Site Care and Site Closure Plan**, respectively. Injection phase testing and monitoring will cover four broad aspects of the geologic sequestration (GS) operation including (1) mechanical integrity testing, (2) operational testing and monitoring, (3) groundwater quality and geochemical monitoring, and (4) CO_2 plume and pressure front tracking.

Table 7-1. 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	[redacted]	First Permeable Zone	[redacted] ft MD	5
In-Zone Monitoring	TCSC_IZM-1 TCSC_IZM-2 TCSC_IZM-3	Vertical	a) [redacted] b) [redacted]	Storage Reservoir	*TCSC_IZM-1*: a) [redacted] b) [redacted] *TCSC_IZM-2*: a) [redacted] b) [redacted] *TCSC_IZM-3*: a) [redacted] b) [redacted]	3
CO_2 Injection	TCSC-1 TCSC-2	Deviated	[redacted]	Storage Reservoir	[redacted]	2
	TCSC-3 TCSC-4 TCSC-5	Deviated	[redacted]	Storage Reservoir	[redacted]	3

[A]Estimated depth of the formation top.

7.2.2.1. Mechanical Integrity Testing

Mechanical integrity testing of injection wells is a key aspect of the TCSC testing and monitoring program. Because each injection well penetrates both storage reservoirs and USDWs, it is critical to demonstrate well integrity to ensure the protection of groundwater resources. Internal and external mechanical integrity will be demonstrated periodically within all CO_2 injection wells throughout the injection phase (**Table 7-2**). The mechanical integrity testing activities will monitor for any leaks in the casing, tubing, or packer (i.e., internal mechanical integrity) as well as fluid flow behind the casing (i.e., external mechanical integrity) to ensure there is no endangerment of local USDWs. For detailed information on the mechanical integrity testing program at TCSC, please reference section **7.3. Mechanical Integrity Testing**.

7.2.2.1. Operational Testing and Monitoring

The operational testing and monitoring program includes CO_2 stream analysis, continuous recording of injection rate, volume, temperature, and pressure along with annulus pressure and fluid volume, quarterly corrosion monitoring, and intermittent pressure fall-off testing. Monitoring operational parameters ensures that TCSC is compliant with Class VI permit conditions, informs AoR reevaluations, and aids in identifying anomalous trends in injection data resultant of changing field conditions and/or loss of containment. The CO_2 injectate stream will be sampled twice per year for chemical analyses immediately downstream of the compression facilities and upstream of all CO_2 injection wells for representative sample exposure. Operational injection parameters such as the injection rate, volume, temperature, and pressure along with the annulus pressure and fluid volume will be continuously monitored for each CO_2 injection well on the shared well pad. Quarterly corrosion monitoring of well components that are to be in contact with the CO_2 injectate stream will also be performed for each CO_2 injection well on the well pad. Lastly, pressure fall-off testing will be performed at least once every five years in each injection well throughout the injection phase to better understand injectivity and reservoir heterogeneity. For detailed information on the operational testing and monitoring activities to be performed throughout the injection phase, please reference section **7.4. Operational Testing and Monitoring**.

7.2.2.2. Groundwater Quality and Geochemical Monitoring

Monitoring the groundwater quality and geochemistry of the above confining zone will demonstrate CO_2 containment and USDW non-endangerment. In the unlikely event of loss of containment from the storage complex, the groundwater quality and geochemical monitoring program strategy will allow for the identification of physical and/or chemical fluid changes associated with any out of zone CO_2 injectate and/or reservoir fluids prior to them reaching overlying USDWs. Five above-zone monitoring wells (TCSC_AZM-(1-5)) will be drilled and strategically completed within the anticipated first permeable zone above the caprock, the Claimed as PBI [redacted]. The above-zone monitoring wells are proposed to be located in areas most informative to the goals of the above-zone groundwater quality and geochemical monitoring strategy. TCSC_AZM-1 will be located on the injection well pad whereas TCSC_AZM-(2-5) will be strategically placed throughout the AoR near Claimed as PBI [redacted] and in areas where groundwater is predominantly sourced from such as the sand and gravel deposits of the Scioto and Teays River Valleys. Please reference **Figure 7-1** for a well section displaying the proposed above-zone monitoring wells completed within the anticipated first permeable zone above the caprock. Please reference **Figure 7-2** for an aerial view of TCSC displaying the location of each above-zone monitoring well relative to project elements.

While loss of containment is unlikely, baseline profiles from pulsed neutron logs (PNLs) will be collected prior to injection so that subsequent pulsed neutron logging can be performed, if needed, to verify and quantify fluids should natural conditions within the above-zone be disturbed; the observed fluids would be used to (1) evaluate the magnitude of loss of containment and (2) generate predictions regarding anticipated impacts on shallow groundwater sources and ecology. For detailed information on groundwater quality and geochemical monitoring of the above confining zone, please reference section **7.5. Groundwater Quality and Geochemical Monitoring**.

Claimed as PBI [redacted]

Figure 7-1. Generalized stratigraphic column and schematic of the injection and monitoring wells at TCSC. This figure is representative to display formations of interest and monitoring strategies. For official well schematics, please reference the Well Construction Plan. *Directly under the TCSC injection site lies Claimed as PBI [redacted]**. **** Claimed as PBI [redacted] **the TCSC injection site but exists elsewhere throughout the area of review.**

Table 7-2. Summary of the injection phase testing and monitoring activities at TCSC.

Monitoring Category & Parameter		Method or Equipment	Location	Injection Phase Frequency[A] (30 Years)	40 CFR Reference
Mechanical Integrity Testing	Internal	Annulus pressure monitoring	TCSC-(1-5)	Continuous	146.88(d) 146.89(a)(1) 146.89(b) 146.91(a)(7) 146.91(b)(1)
	External	DTS fiber-optic or equivalent	TCSC-(1-5)	Once per year	146.88(d) 146.89(a)(2) 146.89(c) 146.90(e) 146.91(a)(7) 146.91(b)(1)
Operational Testing and Monitoring	CO_2 Stream Chemical Analysis	Physical sampling and laboratory analysis	Downstream of CO_2 compression facilities and upstream of TCSC-(1-5)	Twice per year	146.90(a) 146.91(a)(1) 146.91(a)(7)
	Continuous Recording of Injection Rate, Volume, and Temperature	Corolis flow meter or equivalent	Immediately upstream of TCSC-(1-5) on well pad	Continuous	146.88(e)(1) 146.90(b) 146.91(a)(2)
	Continuous Recording of Injection Pressure	(a) Wellhead pressure gauge(s) (b) Downhole pressure gauge(s)	TCSC-(1-5)	Continuous	146.88(e)(1) 146.90(b) 146.91(a)(2)
	Continuous Recording of Annulus Pressure	Wellhead pressure gauge(s)	TCSC-(1-5)	Continuous	146.88(e)(1) 146.90(b) 146.91(a)(2)
	Continuous Recording of Annulus Fluid Volume Added	Annulus monitoring system	TCSC-(1-5) on well pad	Continuous	146.88(e)(1) 146.90(b) 146.91(a)(6)

Monitoring Category & Parameter		Method or Equipment	Location	Injection Phase Frequency[A] (30 Years)	40 CFR Reference
	Corrosion Monitoring	Corrosion coupon(s)	Immediately upstream of TCSC-(1-5) on well pad	Quarterly	146.89(d) 146.90(c) 146.91(a)(7)
	Hydrogeologic Characteristics	Pressure fall-off test	TCSC-(1-5)	Once every five years	146.90(f) 146.91(a)(7)
Groundwater Quality and Geochemical Monitoring	Above-Zone (i.e., First Permeable Zone Above Caprock) Monitoring	a) Fluid sampling and laboratory analysis b) Downhole pressure measurements	TCSC_AZM-(1-5)	a) Quarterly throughout first year of injection, once per year thereafter b) Continuous	146.90(d) 146.91(a)(7)
CO_2 Plume and Pressure Front Tracking	Indirect CO_2 Plume Imaging	Surface seismic (2D or 3D) or equivalent	TCSC site	Year 5, 10, 20, and 30 of injection	146.90(g)(2) 146.91(a)(7)
		Pulsed neutron logging	Select wells	As needed	146.90(g)(2) 146.91(a)(7)
	Direct Pressure Front Tracking	Downhole pressure gauge(s)	TCSC_IZM-(1-3) TCSC-(1-5)	Continuous	146.90(g)(1) 146.91(a)(7)

[A]For pre-injection and post-injection testing and monitoring frequencies, please reference the **Pre-Operational Testing Program** and the **Post-Injection Site Care and Site Closure Plan**, respectively.

7.2.2.3. Carbon Dioxide Plume and Pressure Front Tracking

CO_2 plume and pressure front tracking will be performed across the TCSC site to ensure the injected CO_2 is appropriately stored and moves throughout the storage reservoirs as predicted; the data will be used to validate and/or update model predictions, inform AoR reevaluations, and help define PISC and site closure procedures. Additionally, CO_2 plume and pressure front tracking are integral for protecting USDWs. Plume and pressure front data will be used to identify potential risk areas so they may be mitigated.

CO_2 plume migration throughout the storage reservoirs will be monitored indirectly with repeat surface seismic or equivalent (e.g., 2D or 3D); repeat seismic surveys will image the CO_2 plumes so their development can be tracked throughout the lifespan of the project. Additionally, three in-zone monitoring wells (TCSC_IZM-(1-3)) are proposed to be placed along the outside of the maximum modeled CO_2 extent within the AoR to act as sentry wells. TCSC_IZM-(1-3) will be dual-zone monitoring wells capable of collecting data from both the Claimed as PBI and Claimed as PBI storage reservoirs. The in-zone monitoring wells will primarily be utilized to track the pressure front propagation throughout the storage reservoirs. Additionally, wireline CO_2 detection tools (e.g., PNLs) can be run in the in-zone wells on an as needed basis to verify and help quantify the presence of CO_2 within the storage reservoirs. Please reference **Figure 7-2** for an aerial view of the TCSC site displaying the location of the three in-zone monitoring wells relative to project elements.

7.2.3. Quality Assurance Procedures

A **Quality Assurance and Surveillance Plan** (**QASP**) for all testing and monitoring activities, pursuant to 40 CFR 146.90(k), is provided as **Attachment A** to this **Testing and Monitoring Plan**.

7.2.4. Reporting Procedures

Trillium will report the results of all testing and monitoring activities to the Region 05 UIC Program Director pursuant to 40 CFR 146.91.

7.2.4.1. Semi-Annual Reporting

Pursuant to 40 CFR 146.91(a), Trillium will provide the UIC Program Director with semi-annual reports containing the following:

- Any changes to the physical, chemical, and other relevant characteristics of the carbon dioxide stream from the proposed operating data.
- Monthly average, maximum, and minimum values for injection pressure, flow rate and volume, and annular pressure.
- A description of any event that exceeds operating parameters for annulus pressure or injection pressure specified in the permit.
- A description of any event which triggers a shut-off device required pursuant to 40 CFR 146.88(e) and the response taken.
- The monthly volume and/or mass of the carbon dioxide stream injected over the reporting period and the volume injected cumulatively over the life of the project.
- Monthly annulus fluid volume added.
- The results of monitoring prescribed under 40 CFR 146.90

7.2.4.2. Reporting within 30 Days

Pursuant to 40 CFR 146.91(b), Trillium will provide the results of the following activities to the UIC Program Director within 30 days of occurrence:

- Periodic tests of mechanical integrity.
- Any well workover.
- Any other test of the injection well conducted by Trillium if required by the Director.

7.2.4.3. Reporting within 24 Hours

Pursuant to 40 CFR 146.91(c), Trillium will report the following events within 24 hours of occurrence:

- Any evidence that the injected carbon dioxide stream or associated pressure front may cause an endangerment to a USDW.
- Any noncompliance with a permit condition, or malfunction of the injection system, which may cause fluid migration into or between USDWs.
- Any triggering of a shut-off system (i.e., downhole or at the surface).
- Any failure to maintain mechanical integrity.
- Pursuant to compliance with the requirement at 40 CFR 146.90(h) for surface air/gas monitoring or other monitoring technologies, if required by the Director, any release of carbon dioxide to the atmosphere or biosphere.

7.2.4.4. Advanced Notice of Activities

Pursuant to 40 CFR 146.91(d), Trillium will provide a 30-day notice to the UIC Program Director in advance of the following activities:

- Any planned well workover.
- Any planned stimulation activities, other than stimulation for formation testing conducted under 40 CFR 146.82.
- Any planned test of the injection well conducted by Trillium.

7.2.4.5. Recordkeeping

Pursuant to 40 CFR 146.91(f), Trillium will retain the following records for the time specified:

- All data collected under 40 CFR 146.82 for Class VI permit applications shall be retained throughout the life of the geologic sequestration project and for ten years following site closure.
- Data on the nature and composition of all injected fluids collected pursuant to 40 CFR 146.90(a) shall be retained until 10 years after site closure. The Director may require Trillium to deliver the records to the Director at the conclusion of the retention period.
- Monitoring data collected pursuant to 40 CFR 146.90(b) through (i) shall be retained for ten years after it is collected.
- Well plugging reports, post-injection site care data, including, if appropriate, data and information used to develop the demonstration of the alternative post-injection site care timeframe, and the site closure report collected pursuant to requirements at 40 CFR 146.93(f) and (h) shall be retained for ten years following site closure.

Claimed as PBI

Figure 7-2. 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. For a zoomed in view of the injection well pad, please reference Figure 7-3. CO_2 plume and pressure front boundaries represent the combined maximum extent from both the Claimed as PBI **and** Claimed as PBI **storage reservoirs.**

7.3. MECHANICAL INTEGRITY TESTING

Trillium is committed to maintaining injection well mechanical integrity throughout the lifetime of the project. A well has mechanical integrity if:

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

Internal and external mechanical integrity will be demonstrated in all TCSC injection wells prior to injection (40 CFR 146.87(a)(4)), during the injection phase (40 CFR 146.88(d), 146.89(b), 146.89(c), and 146.90(e)), and prior to well plugging after injection has ceased (40 CFR 146.92(a)). Internal mechanical integrity will be demonstrated prior to injection with a standard annulus pressure test followed by continuous monitoring of annulus pressure and fluid volume (i.e., pressure and volume between the tubing and long-string casing) throughout the injection phase. External mechanical integrity will also be demonstrated prior to injection, throughout the active injection phase, and prior to injection well plugging through the analysis of distributed temperature sensing (DTS) data or equivalent. **Table 7-3** summarizes the internal and external mechanical integrity test (MIT) methods, locations, and frequencies. Further details on these methods and their frequencies are discussed throughout the following subsections.

7.3.1. Testing Location and Frequency

Prior to injection, internal mechanical integrity for all TCSC injection wells will be demonstrated once with an annulus pressure test pursuant to 40 CFR 146.87(a)(4)(i). Following this initial pressure test, internal mechanical integrity will be demonstrated throughout all injection wells by continuously monitoring the annulus pressure and fluid volume pursuant to 40 CFR 146.89(b).

Pursuant to 40 CFR 146.87(a)(4)(iii), external mechanical integrity will be demonstrated once prior to injection within all injection wells via analysis of DTS data. Upon injection commencement and throughout the injection phase, DTS data will be used to demonstrate external mechanical integrity once per year within all injection wells, pursuant to 40 CFR 146.89(c)(2) and 40 CFR 146.90(e). Additionally, external mechanical integrity will be demonstrated once prior to the plugging of each injection well pursuant to 40 CFR 146.92(a).

Table 7-3. Summary of the injection phase internal and external mechanical integrity activities to be performed at TCSC.

Monitoring Category	Method or Equipment	Location	Injection Phase Frequency (30 Years)
Internal MIT	Continuous annulus pressure and fluid volume monitoring	TCSC-(1-5)	Continuous
External MIT	DTS fiber-optic or equivalent	TCSC-(1-5)	Once per year

7.3.2. Internal MIT Details

Internal mechanical integrity tests are designed to detect significant leaks in the casing, tubing, or packer (40 CFR 146.89(a)(1)). Internal mechanical integrity will be demonstrated once prior to injection via a standard annulus pressure test throughout all injection wells (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 [1]. If there is no significant change in pressure for the duration of the test period, the well will have demonstrated internal mechanical integrity. For additional information on annulus pressure testing such as specific testing times and pressure criteria, please reference section **5.2.4.1 Internal Mechanical Integrity** of the **Pre-Operational Testing Program**. Following this initial pressure test, internal mechanical integrity will be demonstrated via continuously monitoring the annulus pressure and fluid volume (40 CFR 146.89(b)). For additional information on the continuous recording of operational parameters such as injection and annulus pressures, please reference section **7.4.2. Continuous Recording of Injection Rate, Volume, Temperature, and Pressure** and **7.4.3. Continuous Recording of Annulus Pressure and Fluid Volume**, respectively.

7.3.3. External MIT Details

External mechanical integrity tests are designed to detect fluids that have escaped from the wellbore which could migrate into USDWs (40 CFR 146.89(a)(2)). External mechanical integrity will be demonstrated throughout all injection wells through the analysis of DTS fiber-optic measurements. DTS fiber-optic cables will be deployed in injection wells TCSC-(1-5) from at least the base of the caprock to the surface. Similar to standard temperature logging, the fiber-optic will record a temperature profile throughout the borehole which can be used to detect leaks in casing and fluid movement adjacent to the wellbore based on the principal that fluid leaking will produce temperature anomalies. DTS fiber-optic cables provide various advantages over standard temperature logging such as reliability in hostile environments and high spatial, time, and temperature resolution [2]. While the DTS fiber-optic cables can record temperature continuously (e.g., one measurement per minute, five minutes, etc.), official external MITs will involve shutting in each CO_2 injection well for a sufficient period of time to allow temperature to change toward static geothermal conditions [1]. DTS measurements will then be analyzed for temperature anomalies indicative of leaks in casing and fluid movement along the wellbore. Therefore, DTS measurements will be used to verify the external mechanical integrity of all CO_2 injection wells throughout the lifespan of the TCSC project pursuant 40 CFR 146.89(c)(2). 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 146.89(c)(1) and (2), respectively.

7.3.4. MIT Reporting Requirements

Trillium will comply with all notification and reporting requirements described in section **7.2.4. Reporting Procedures** of this plan. Should loss of mechanical integrity be demonstrated through monitoring, the UIC Program Director will be notified within 24 hours and all steps necessary will be taken to determine whether there may have been a release of CO_2 injectate and/or reservoir fluids into any unauthorized zones. If it is determined that substantial endangerment to public health or the environment exists from any fluid movement out of the intended storage complex, Trillium will implement the **Emergency and Remedial Response Plan** (40 CFR 146.94). If a well were to lose mechanical integrity, well integrity will be restored and demonstrated prior to resuming injection or plugging operations; the new demonstration of mechanical integrity will be reported to the UIC Program Director within 30-days of the test. Additionally, in the next semi-annual report, Trillium will document the type of failure, the cause, and the required repairs to restore well integrity.

7.3.5. MIT Gauges and Equipment

Pressure gauges and systems used for internal mechanical integrity testing and monitoring will be calibrated according to the manufacturer's specifications. DTS fiber-optic cables used to collect data that will demonstrate external mechanical integrity will be carefully calibrated according to the manufacturer's specifications to provide reliable temperature measurements. Any wireline logging tools utilized for mechanical integrity demonstrations will be calibrated according to the service company's standard operating procedures. For additional details on wellhead gauge and DTS fiber-optic specifications and sensitivities, please reference section **7A.2.3.1 Method Sensitivity and Precision** of the **Quality Assurance and Surveillance Plan**.

7.4. OPERATIONAL TESTING AND MONITORING

7.4.1. Carbon Dioxide Stream Analysis

Throughout the injection phase, the CO_2 stream will be analyzed to yield data representative of its chemical and physical characteristics pursuant to 40 CFR 146.90(a). Analyzing the CO_2 stream and its constituents will help evaluate potential reactions between the injectate and formation solids and fluids. CO_2 to be injected at the TCSC site will be sourced from the Claimed as PBI [redacted]

7.4.1.1. Sampling Method, Location, and Frequency

The CO_2 stream will be monitored throughout the injection phase to a sufficient frequency to yield data representative of its chemical and physical characteristics pursuant to 40 CFR 146.90(a). Baseline parameters will be established at the start of injection and monitoring will occur throughout the injection phase via physical CO_2 stream sampling and laboratory analysis. CO_2 stream samples will be collected from one sampling port located downstream of the CO_2 compression facilities and upstream of all injection wells to ensure representative sample collection (**Figure 7-3**). Samples will be collected in gas cylinders or equivalent and sent to an appropriate laboratory for chemical analysis. Because the composition of the CO_2 stream is expected to be pure (>99% CO_2) and not vary throughout the lifespan of the project, physical sampling and laboratory analysis will occur twice per year. All results of CO_2 stream analyses will be submitted in semi-annual reports pursuant to 40 CFR 146.91(a). In the event of unplanned disruptions to permitted injection activities that may affect the chemical and physical composition of the CO_2 stream, the frequency of analysis and/or reporting will increase to confirm there are no significant changes to the CO_2 injectate and that injection operations are continuing as permitted.

7.4.1.2. Analytical Parameters

The CO_2 injectate stream is expected to have a mol% CO_2 concentration Claimed as PBI [redacted] with the additional chemical constituents listed in **Table 7-4**. While CO_2 stream composition is not expected to vary throughout the lifespan of TCSC, the specifications will be further refined, if necessary, Claimed as PBI [redacted] and

CO_2 capture equipment is operational; the list of parameters will be altered if analysis of the CO_2 stream demonstrates additional constituents are to be considered. Amendments to this plan will be sent to the UIC Program Director for approval. Additionally, the physical characteristics of the CO_2 injectate will be monitored as described in section **7.4.2. Continuous Recording of Injection Rate, Volume, Temperature, and Pressure** of this plan.

Table 7-4. Summary of the expected physical and chemical characteristics of the CO_2 injectate stream at TCSC.

Claimed as PBI [redacted]

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

[B]Represents pressure at the CO_2 outlet. Claimed as PBI [redacted]

[C]Represents the temperature the injectate stream Claimed as PBI [redacted]

7.4.1.3. Laboratory to be Used and Chain of Custody Procedures

The CO_2 stream will be physically sampled on the TCSC site and sent to an approved laboratory that is capable of measuring the parameters listed in **Table 7-4**. Once an appropriate laboratory is selected to perform the CO_2 injectate analysis such as Core Laboratories, Isotech, or an equivalent laboratory, a form will be used for chain of custody documentation to ensure organization and that all activities are archived. For additional information on sample preservation and handling, chain of custody, and quality assurance, please reference section **7.2 Data Generation and Acquisition** of the **Quality Assurance and Surveillance Plan**.

7.4.2. Continuous Recording of Injection Rate, Volume, Temperature, and Pressure

The target injection rates and expected wellhead pressures and temperatures for each CO_2 injection well are listed in **Table 7-5**. Continuous recording devices (**Table 7-6**) will be installed and utilized to continuously monitor the injection rate, volume, temperature, and pressure of the CO_2 injectate stream pursuant to 40 CFR 146.88(e)(1) and 146.90(b). Continuous recording of operational parameters ensures TCSC is operating safely, efficiently, and as permitted.

Table 7-5. Summary of expected CO_2 injection well operational parameters.

Injection Well	Target Injection Rate (MMtpa)	Wellhead Pressure[A] (psi)	Wellhead Temperature (°F)
TCSC-1	Claimed as PBI [redacted]	[redacted]	[redacted]
TCSC-2	Claimed as PBI [redacted]	[redacted]	[redacted]
TCSC-3	Claimed as PBI [redacted]	[redacted]	[redacted]
TCSC-4	Claimed as PBI [redacted]	[redacted]	[redacted]
TCSC-5	Claimed as PBI [redacted]	[redacted]	[redacted]

[A]Wellhead pressures subject to change and slightly increase based on downhole conditions.

Injection rate, volume, and temperature will be monitored with mass flow meters, such as Coriolis flow meters, immediately upstream of each CO_2 injection well on the shared well pad; the specific location on the well pad will be determined in collaboration with the device's manufacturer to ensure the most accurate and precise measurements. Flow meters will be pressure/temperature compensated and calibrated to the manufacturer's specifications. Flow rate data will be used to determine the cumulative mass of CO_2 injected and to confirm compliance with the operational requirements of the Class VI UIC permit. For additional information on the flow meters to be utilized, please reference section **7A.2.3.1 Method Sensitivity and Precision** of the **Quality Assurance and Surveillance Plan**.

Injection pressure will be continuously monitored at the surface using wellhead pressure gauges ported to the injection tubing of each CO_2 injection well. Additionally, downhole injection pressure and temperature measurements will be recorded using permanent downhole pressure/temperature gauges ported through the packer and into the injection tubing within the storage reservoirs. For additional information on the surface and downhole gauges to be utilized, please reference section **7A.2.3.1 Method Sensitivity and Precision** of the **Quality Assurance and Surveillance Plan**.

A distributed control system (DCS) will be utilized to control operational parameters to ensure they remain within their permitted ranges. A supervisory control and data acquisition (SCADA) system will be utilized for real-time monitoring and project decision making; the SCADA will be utilized to monitor operations and identify any anomalous trends in data. If specific parameters are observed to exceed their allowable operating limits, an automatic alarm will be triggered, operations will be shut down, and an investigation will be performed to identify the cause of the shutoff pursuant to 40 CFR 146.88(e) and 146.88(f).

Please reference **Figure 7-3** for a generalized schematic of the well pad and where operational monitoring equipment may be located. Official equipment locations and schematics will be determined in subsequent phases during advanced design engineering and/or well construction.

Table 7-6. Summary of the devices, locations, and frequencies for continuous monitoring of injection parameters at TCSC.

Monitoring Parameter	Device	Location	Frequency
Injection Rate	Coriolis flow meter or equivalent	Immediately upstream of TCSC-(1-5) on well pad	Continuous
Injection Volume	Coriolis flow meter or equivalent	Immediately upstream of TCSC-(1-5) on well pad	Continuous
Injection Temperature	(a) Coriolis flow meter or equivalent (b) Downhole temperature gauge(s)	(a) Immediately upstream of TCSC-(1-5) on well pad (b) TCSC-(1-5)	Continuous
Injection Pressure	(a) Wellhead pressure gauge(s) (b) Downhole pressure gauge(s)	TCSC-(1-5)	Continuous
Annulus Pressure	Wellhead pressure gauge(s)	TCSC-(1-5)	Continuous
Annulus Fluid Volume	Annulus monitoring system	TCSC-(1-5) on well pad	Continuous

Claimed as PBI

[redacted]

Figure 7-3. Aerial view of the TCSC injection well pad. The map is a generalized example showing locations of where continuous monitoring equipment may be located. Official designs and schematics will be finalized in subsequent phases during advanced design engineering and/or well construction.

7.4.3. Continuous Recording of Annulus Pressure and Fluid Volume

Pursuant to 40 CFR 146.88(e)(1) and 146.90(b), annulus pressure and fluid volume will be continuously recorded throughout the injection phase. Monitoring the annulus pressure and fluid volume of each CO_2 injection well will demonstrate internal mechanical integrity throughout the injection phase between the yearly external mechanical integrity analyses.

Annulus pressure will be monitored at the surface with wellhead pressure gauges ported to the annulus of each CO_2 injection well. Fluid volume indicators, located on the shared well pad, will be used to monitor the annulus fluid volume added to each CO_2 injection well. The following procedure will be used to monitor the annulus and to mitigate the potential for any unpermitted fluid movement into or out of the wellbore:

- Pursuant to 40 CFR 146.88(c), the annulus (i.e., the space between the tubing and long string casing) will be filled with a non-corrosive fluid approved by the director.

- The pressure within the annulus immediately above the packer will exceed the injection pressure, pursuant to 40 CFR 146.88(c).
- A pressure differential of at least 150 psi will be maintained between the injection tubing and annulus immediately above the packer.

Figure 7-4 displays an example of a process and instrument diagram (P&ID) used for an injection well annulus protection system. The system will consist of a surface pressure gauge ported to the annulus on the wellhead, a pressurized annulus fluid reservoir (i.e., annulus head tank), pressure regulators, and a tank fluid level indicator. The system will maintain annulus pressure by controlling the pressure on the annulus head tank using compressed nitrogen. The annulus pressure system will allow for the identification of significant changes in annulus pressure and/or the fluid volume which may prompt mechanical integrity investigations. Once an appropriate vendor is selected and the annulus monitoring system's design is finalized, a specific P&ID will be provided to the UIC Program Director for each CO_2 injection well.

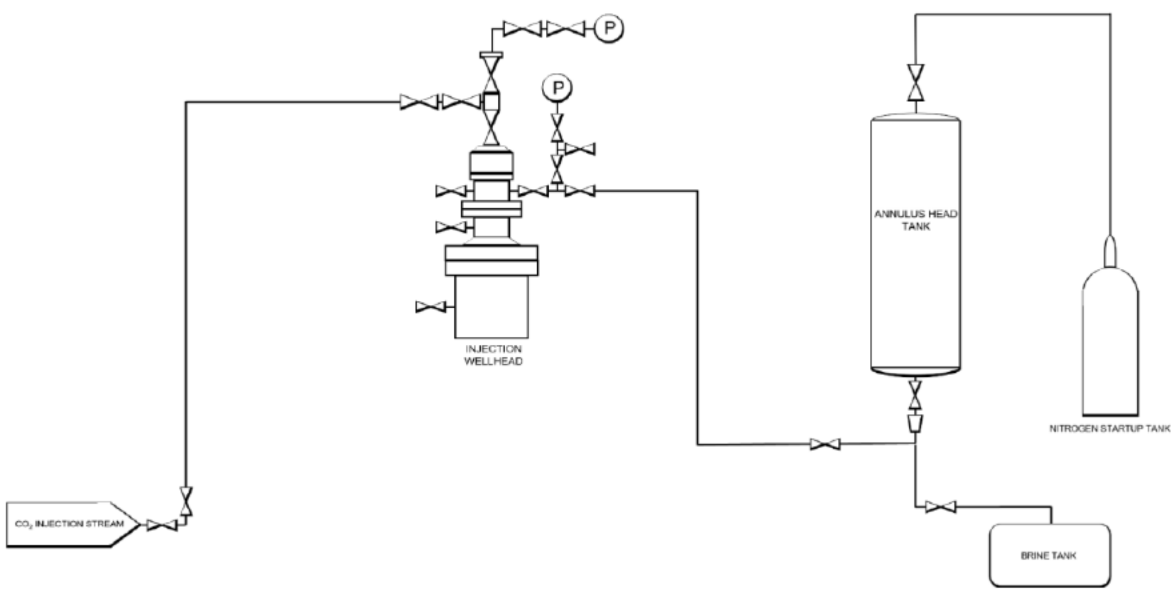

Figure 7-4. Example of a pressure monitoring system that can be used to continuously maintain and monitor annulus pressure and fluid volume added.

7.4.4. Corrosion Monitoring

To meet the requirements of 40 CFR 146.90(c), 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 other signs of corrosion. Corrosion monitoring ensures well components meet the minimum standards for material strength and performance pursuant to 40 CFR 146.86(b).

7.4.4.1. Monitoring Method, Location, and Frequency

Corrosion will be monitored using corrosion coupons a part of a pipeline bypass or "loop system", pursuant to 40 CFR 146.90(c)(1), located prior to each CO_2 injection well on the shared well pad (**Figure 7-3**). The system will be located prior to each wellhead to provide representative exposure to the CO_2 composition, pressure, and temperature that will be observed at the wellhead and in the injection tubing. Corrosion coupon sampling and analysis will be performed quarterly pursuant to 40 CFR 146.90(c). For a summary of the corrosion monitoring program, please reference **Table 7-7**.

Table 7-7. 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	Quarterly
Injection Tubing	[redacted], premium connection		
Wellhead	Carbon, alloy, or stainless steel		
Packers	[redacted], VAM coupling		

7.4.4.2. Monitoring Details

Samples of materials used in the construction of wells that will encounter CO_2 will be included in the corrosion monitoring program (**Table 7-7**). The system will consist of a “loop” or parallel section of pipe made of the same material as the rest of the pipeline. Corrosion coupons will then be inserted into a flow-through pipe arrangement attached to the main-line section of pipeline for representative exposure to CO_2 composition, pressure, and temperature. During corrosion coupon sampling, the CO_2 stream will be routed through the bypass section of pipeline while the main-line section is shut-in to allow sampling to be performed without shutting down operations.

The corrosion coupons will be photographed, visually inspected, dimensionally measured, and weighted prior to initial exposure for baseline measurements. Coupons will be handled and evaluated for corrosion using the NACE RP0775-2023 [3] standard or a similarly accepted practice for preparing, cleaning, and evaluating corrosion test specimens. The corrosion rate will be calculated as the weight loss during the exposure period divided by the duration of exposure (i.e., weight loss method). Additionally, based on the corrosion coupon analysis, downhole wireline logs may be run for further inspection of the casing and tubing pursuant to 40 CFR 146.89(d).

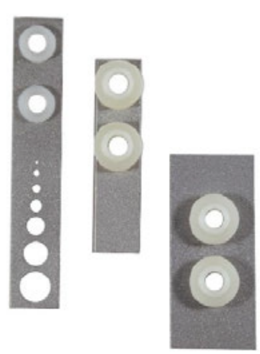

Figure 7-5. Example of corrosion coupons that will be inserted into the pipeline for CO_2 stream exposure [4].

7.4.5. Pressure Fall-Off Testing

Pressure fall-off tests, pursuant to 40 CFR 146.90(f), will be performed in each CO_2 injection well intermittently throughout the TCSC project to better understand the hydrogeologic characteristics of the storage reservoirs. Pressure fall-off tests are designed to measure formation properties, such as transmissivity, in the vicinity of the injection well to verify large-scale injectivity and to identify the presence of flow boundaries that could impact injectivity. The results of pressure fall-off tests will be used to confirm site characterization information, ensure operating parameters are optimal for downhole conditions, inform AoR reevaluations, and verify the injection zones are responding as predicted.

7.4.5.1. Testing Location and Frequency

Pressure fall-off tests will be performed in each CO_2 injection well throughout the life of the TCSC project. Prior to injection, pressure fall-off tests will be conducted in each injection well once for baseline measurements. Throughout the injection phase, pressure fall-off tests will be performed in each injection well at least once every five years (**Table 7-8**).

Table 7-8. Summary of injection phase pressure fall-off testing at TCSC.

Monitoring Parameter	Monitoring Method	Location	Frequency
Hydrogeologic Testing	Pressure fall-off test	TCSC-(1-5)	At least once every five years

7.4.5.2. Testing Details

Best practices for pressure fall-off testing will be followed such as those discussed in EPA Region 06 UIC Pressure Falloff Testing Guideline [5]. The pressure fall-off tests performed will include a period of injection followed by a period of no injection or shut-in. Prior to the shut-in portion of the test, a constant injection rate will be maintained for a suitable amount of time to produce a measurable pressure transient. If the injection rate causes relatively large changes in bottomhole pressure, the rate will be adjusted. Following the injection period, the well being tested 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.

All pressure fall-off data will be collected using downhole pressure gauges that will be calibrated according to manufacturer specifications. For additional information on the downhole pressure gauges to be deployed in each CO_2 injection well, please reference section **7A.2.3.1 Method Sensitivity and Precision** of the **Quality Assurance and Surveillance Plan**.

7.5. GROUNDWATER QUALITY AND GEOCHEMICAL MONITORING

The primary goal of Trillium's **Testing and Monitoring Plan**, and specifically the above-zone groundwater quality and geochemical monitoring program, is to protect local USDWs. Groundwater quality and geochemical monitoring, pursuant to 40 CFR 146.90(d), will be performed in all above-zone monitoring wells completed within the Claimed as PBI (i.e., anticipated first permeable zone above the caprock) to demonstrate CO_2 containment and USDW non-endangerment. In the unlikely event of loss of containment from the storage complex, the groundwater quality and geochemical monitoring strategy within the [redacted] will allow for early detection of out of zone CO_2 and/or reservoir fluids prior to them reaching overlying USDWs. The following subsections describe the injection phase groundwater quality and geochemical monitoring details; for the baseline and post-injection groundwater quality and geochemical monitoring strategies, please reference the **Pre-Operational Testing Program** and **Post-Injection Site Care and Site Closure Plan**, respectively.

[redacted]

7.5.1. Monitoring Location and Frequency

All above-zone monitoring wells (TCSC_AZM-(1-5)) are proposed to be completed within the [redacted]. The [redacted] is the [redacted] within the AoR. The [redacted], and specifically the [redacted], are often referred to as the [redacted] by drillers when they encounter a porous zone [6] [7] [8]. It is anticipated that the [redacted] is the first permeable zone above the caprock and therefore the most ideal above-zone formation for groundwater quality and geochemical monitoring [1]. However, permeability is difficult to predict in carbonates and the permeable zone may be continuous, localized, or non-existent. If throughout drilling operations it is discovered that the [redacted] is not as porous/permeable as literature anticipates, above-zone monitoring wells will either be completed within the [redacted] (i.e., [redacted] where drillers have encountered the [redacted]), the [redacted] or the sand and gravel deposits of the Scioto and Teays River Valleys which yield the most freshwater [10]).

The proposed locations of the five above-zone monitoring wells to be completed within the [redacted] are displayed in **Figure 7-2** relative to project elements. The above-zone monitoring wells will be strategically located in sensitive areas throughout the AoR to provide information demonstrating CO_2 containment and USDW non-endangerment. TCSC_AZM-1 will be located on the injection well pad to monitor groundwater quality and geochemistry underlying the CO_2 injection site. TCSC_AZM-2 has been placed in the [redacted] the AoR within the Scioto River Valley between [redacted] and the village of Piketon; this well has been placed to monitor the groundwater quality and geochemistry underlying the freshwater sand and gravel deposits of the Scioto River Valley Aquifer System where groundwater is predominantly sourced from. TCSC_AZM-3 has been placed in the [redacted] region of the AoR within the ancient Teays River Valley near [redacted]; this well has been placed to monitor the groundwater quality and geochemistry underlying the shallow sand and gravel deposits in which groundwater is sourced from within the Teays River Valley. TCSC_AZM-4 has been placed along the [redacted] extent of the CO_2 plume within the AoR near [redacted] AoR extent. TCSC_AZM-4 will confirm CO_2 containment and USDW non-endangerment near [redacted] TCSC_AZM-5 has been placed in the [redacted] region of the AoR within the Scioto River Valley to monitor the groundwater quality and geochemistry underlying the freshwater sand and gravel deposits of the Scioto River Valley Aquifer System.

Groundwater fluid samples will be collected from all above-zone monitoring wells and evaluated quarterly throughout the first year of injection. Samples obtained throughout the first year of injection will be collected during the same months as the quarterly baseline fluids samples to account for seasonal variations. Once four consecutive sampling and analysis events are performed without variation, of which threshold values will be determined from baseline results, above-zone sampling frequency will decrease to once per year for the remainder of the injection phase. The yearly sampling and analysis event will occur during the same month as the previous year's event to account for seasonal variations. If variation is observed between yearly sampling events, quarterly sampling will be resumed until four consecutive events without variation are recorded. Groundwater monitoring data will be submitted in semi-annual reports pursuant to 40 CFR 146.91(a)(7). The planned monitoring methods, locations, and frequencies for groundwater quality and geochemical monitoring throughout the injection phase are summarized in **Table 7-9**.

Table 7-9. Summary of the above confining zone monitoring activities at TCSC.

Monitoring Parameter	Method	Target Formation	Location	Frequency
Groundwater Quality and Geochemical Monitoring	a) Fluid sampling and laboratory analysis b) Downhole pressure measurements	Claimed as PBI (i.e., first permeable zone above caprock)	TCSC_AZM-(1-5)	(a) Quarterly throughout first year of injection, once per year thereafter (b) Continuous

7.5.2. Sampling Methods

Groundwater fluid samples will be collected from the Claimed as PBI (i.e., first permeable zone above the caprock) in TCSC_AZM-(1-5) via well purging such as low-flow purging or an equivalent method [11]. Well purging ensures that the groundwater being sampled is representative of the formation water quality. Fluid samples will be collected, appropriately stored in sampling containers, and sent to an approved laboratory for analysis. In addition to fluid sampling and analysis, the Claimed as PBI formation pressure will be monitored with downhole pressure gauges in all above-zone monitoring wells. Monitoring formation pressures will allow for the identification of any anomalous pressures potentially associated with unexpected out of zone CO_2 and/or reservoir fluids and therefore act as indirect water quality indicators. For additional information on above-zone fluid sampling methods, equipment, and procedures, please reference sections **7A.2.2 Sampling Methods** through **7.A.2.5 Analytical Methods** of the **Quality Assurance and Surveillance Plan**.

7.5.3. Analytical Parameters

Fluid samples collected from the Claimed as PBI will be analyzed for the geochemical parameters listed in **Table 7-10**. The groundwater sampling suite will include analyzing various fluid physical and chemical properties, major ions, gases, and unique carbon and hydrogen isotopes. The parameters listed in **Table 7-10** can be used as water quality indicators and tracers to determine whether out of zone fluids have been introduced into the above-zone monitoring formation. The concentration of parameters and their threshold variations will be determined from baseline fluid sampling and analysis. Depending on baseline results, parameters with non-significant impacts on project monitoring will be removed from the above-zone fluid sampling and analysis program. If baseline testing reveals the need for additional parameters to be monitored, they will be added to the program and analyzed in future events.

7.5.4. Laboratory to be Used and Chain of Custody Procedures

Groundwater sampling, sample preservation and handling, chain of custody, and quality assurance will be performed in accordance with the methods and procedures described in section **7.2 Data Generation and Acquisition** of the **Quality Assurance and Surveillance Plan**. The most appropriate analytical method will be determined for each parameter in collaboration with the selected analytical laboratory. Specific methods and/or procedures chosen for fluid analysis will be provided to the UIC Program Director.

Table 7-10. Summary of the analytical parameters and methods for above confining zone groundwater samples at TCSC.

Parameters[A]	Analytical Methods[B]
Formation: Claimed as PBI *(First Permeable Zone Above the Caprock)*[C]	
Major Cations	ICP-AES, ICP-OES, ICP-MS, or equivalent *(EPA 6000 Series [12], EPA 200.7 [13], or equivalent)*
Major Anions	Ion Chromatography, Spectroscopy, or equivalent *(EPA 300.0 [14], EPA 300.1 [15], SM 4500 Series [16], or equivalent)*
Ammonia Nitrogen	Colorimetry, Titration, or equivalent *(EPA 350.1 [17], EPA 350.2 [18], or equivalent)*
Dissolved CO_2	Coulometric Titration, Gas Sensing Electrode, or equivalent *(ASTM D513-16 [19] or equivalent)*
Total Dissolved Solids	Gravimetry or equivalent *(EPA 160.1 [20], SM 2540C [21], ASTM D5907-18 [22], or equivalent)*
Alkalinity	pH Meter or equivalent *(SM 2320B [23], ASTM D3875-15 [24] or equivalent)*
pH	pH Meter or equivalent *(EPA 150.1 [25], SM4500H+B [26], ASTM D1293-18 [27], or equivalent)*
Temperature	Thermocouple or equivalent *(SM 2550B [28] or equivalent)*
Conductivity	Conductivity Meter or equivalent *(EPA 120.1 [29], SM 2510B [30], ASTM D1125-23 [31], or equivalent)*
Density	Pycnometer, Hydrometer, Density Meter, or equivalent *(ASTM D1429-13 [32], ASTM D1480-21 [33], ASTM D4052-22 [34], 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 ^3H 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.

7.6. CARBON DIOXIDE PLUME AND PRESSURE FRONT TRACKING

Pursuant to 40 CFR 146.90(g), the CO_2 plume and pressure front tracking activities have been designed to (1) monitor the free-phase CO_2 plume location and its extent, (2) track the pressure development within the storage complex, (3) validate the computational model and inform AoR reevaluations, (4) help define PISC and site closure procedures, and (5) protect USDWs by demonstrating that operations are not leading reservoir CO_2 and/or brine loss of containment. The activities to be performed to indirectly track the CO_2 plume and directly track the pressure front are summarized in **Table 7-11**. **Figure 7-6** displays the CO_2 plume and pressure front development within the [redacted] throughout the injection phase whereas **Figure 7-7** displays the CO_2 plume and pressure front development within the [redacted] throughout the injection phase.

Table 7-11. CO_2 plume and pressure front monitoring activities at TCSC.

Target Formation	Method	Location	Frequency
Indirect CO_2 Plume Tracking			
[redacted]	Surface seismic (2D or 3D) or equivalent	TCSC site	Year [redacted] of injection
	Pulsed neutron logging	Select wells	As needed
[redacted]	Surface seismic (2D or 3D) or equivalent	TCSC site	Year [redacted] of injection
	Pulsed neutron logging	Select wells	As needed
Direct Pressure Front Tracking			
[redacted]	a) Wellhead pressure gauge(s) b) Downhole pressure gauges(s)	TCSC_IZM-(1-3) TCSC-(1-5)	Continuous
[redacted]	a) Wellhead pressure gauge(s) b) Downhole pressure gauges(s)	TCSC_IZM-(1-3) TCSC-(1-5)	Continuous

7.6.1. Carbon Dioxide Plume Monitoring Method, Location, and Frequency

The CO_2 injected at the TCSC site will be tracked throughout the storage reservoirs via surface seismic or equivalent (40 CFR 146.90(g)(2)). Repeat seismic surveys, such as 3D surveys (often referred to as 4D or time-lapse surveys), can indirectly image the subsurface to monitor CO_2 plume migration and estimate its saturation. To image the CO_2 plume, a seismic survey will be conducted prior to injection as a baseline and repeat surveys will be performed at year [redacted] of injection. Seismic surveys are to be conducted at a higher frequency early in the injection phase to ensure the CO_2 plume is being appropriately stored within the [redacted] and [redacted] storage reservoirs. [redacted]

In addition to seismic imaging, PNL tools will be run in all project wells prior to injection operations. PNLs can then be utilized on an as needed basis throughout the injection phase in select wells as CO_2 detection tools. PNL tools can be run throughout the storage reservoirs in the in-zone monitoring wells to verify the presence and extent of the CO_2 plume or they could be utilized in formations above the confining zone in the unlikely event CO_2 and/or reservoir fluid loss of containment is detected to verify its vertical location and saturation.

7.6.2. Carbon Dioxide Plume Monitoring Details

3D seismic surveys involve generating energy waves at the surface that propagate down throughout the subsurface. Waves are reflected off subsurface features where there are changes in acoustic impedance (i.e., product of bulk density and wave velocity) such as between rock and CO_2-saturated rock, the latter of which seismic waves travel slower through. Reflected waves are then detected at the surface and processed into images so that the subsurface can be interpreted in 3D.

Because there are differences in acoustic impedance between rock and CO_2-saturated rock, seismic surveys are often the predominant CO_2 plume monitoring technique for GS operations (e.g., Sleipner project has been utilizing repeat 3D seismic for CO_2 plume monitoring for 20 years [35]). However, there are various factors that may affect 3D surface seismic; according to a 2020 study on seismic monitoring sensitivities conducted by the DOE [36], CO_2 plume detection is affected by (1) the depth of the CO_2 plume, (2) the saturation of CO_2, (3) the surrounding lithology, and (4) the seismic acquisition parameters. In order to image CO_2 with 3D seismic, repeatability between surveys is crucial for accurate interpretation. Seismic feasibility studies including fluid substitution modeling and seismic raytracing will be performed for the TCSC site to determine the optimal seismic acquisition parameters that will allow for the most accurate CO_2 plume imaging over time.

In addition to seismic imaging, CO_2 detection tools such as wireline PNL tools can be utilized for CO_2 plume monitoring. PNL tools emit high-energy neutrons into the formation resulting in gamma rays that can be detected by the tool and processed to estimate fluid saturations. PNL tools are sensitive to changes in reservoir fluids and can therefore be used to quantify CO_2 saturation, detect the arrival of the CO_2 plume front, and detect out of zone CO_2 migration [37]. PNLs will be utilized on an as needed basis within the in-zone monitoring wells to verify the CO_2 plume extent throughout the storage reservoirs or in the above-zone monitoring wells to quantity out of zone fluids in the unlikely event loss of containment is detected.

7.6.3. Pressure Front Monitoring Method, Location, and Frequency

The elevated pressure front evolution across the TCSC site will be directly monitored using downhole pressure gauges pursuant to 40 CFR 146.90(g)(1). Downhole pressure gauges will be located in all CO_2 injection and in-zone monitoring wells and will continuously record the formation pressures of the Claimed as PBI and Claimed as PBI storage reservoirs. Downhole pressure measurements will inform operational parameters and the computational model to ensure TCSC is operating as permitted and that models are accurately predicting the migration of the CO_2 injectate. Wellhead pressure gauges will also be installed on all CO_2 injection and in-zone monitoring wells to provide backup measurements should they be needed.

7.6.4. Pressure Front Monitoring Details

Electronic downhole pressure gauges will be deployed in all CO_2 injection and in-zone monitoring wells to track the elevated pressure front across the TCSC site. Downhole gauges deployed in the CO_2 injection wells will provide pressure measurements from the Claimed as PBI (TCSC-(1-2)) and Claimed as PBI (TCSC-(3-5)) storage reservoirs that will guide operational parameters. Multiple downhole gauges will be deployed in the in-zone monitoring wells (TCSC_IZM-(1-3)) to collect reservoir pressures from both storage reservoirs to track pressure front propagation throughout time. For downhole gauge specifications, please reference section **7A.2.3.1 Method Sensitivity and Precision** of the **Quality Assurance and Surveillance Plan**.

In addition to directly tracking the elevated pressure front associated with CO_2 injection operations throughout the storage reservoirs, downhole pressure will be monitored via downhole gauges in all above-zone monitoring wells completed within the Claimed as PBI. Monitoring pressure within the Claimed as PBI will allow for the detection of any anomalous pressures that may be associated with unexpected out of zone CO_2 and/or reservoir fluids and therefore act as an indirect water quality indicator. For additional information on above confining zone monitoring, please reference section **7.5. Groundwater Quality and Geochemical Monitoring**.

Claimed as PBI

Figure 7-6. Aerial view of TCSC depicting the location of injection and monitoring wells relative to the Claimed as PBI **CO_2 plume and pressure front evolution throughout the injection phase.**

Claimed as PBI [redacted]

Figure 7-7. Aerial view of TCSC depicting the location of injection and monitoring wells relative to the Claimed as PBI [redacted] CO_2 plume and pressure front evolution throughout the injection phase.

7.7. REFERENCES

[1] U.S. EPA, “Geologic Sequestration of Carbon Dioxide, Underground Injection Control (UIC) Program Class VI Well Testing and Monitoring Guidance,” *EPA 816-R-13-001*, 2013.

[2] C. Buecker, S. Grosswig, “Distributed temperature sensing in the oil and gas industry – insights and perspectives,” *Oil Gas European Magazine*, pp. 209-215, 2017.

[3] *Preparation, Installation, Analysis, and Interpretation of Corrosion Coupons in Hydrocarbon Operations*, NACE-SP0775-2023, 2023.

[4] Pacific Sensor. “Introduction to Corrosion Coupons.” PacificSensor.com. Accessed 2024. [Online.] Available: https://www.pacificsensor.com/corrosion-coupon.

[5] U.S. EPA, “UIC Pressure Falloff Testing Guideline,” *EPA Region* 6, rev. 2, 2002.

[6] A.L. Horvath, “Relationships of Middle Silurian Strata in Ohio and West Virginia,” *The Ohio Journal of Science*, vol. 69, no. 6, pp. 321-342, 1969.

[7] A. Janssens, “Catalog of Oil and Gas Wells in “Newburg” (Silurian) of Ohio,” *Information Circular*, no 42, 1975.

[8] M.L. Strobel, E.F. Bugliosi, “Areal Extent, Hydrogeologic Characteristics, and Possible Origins of the Carbonate Rock Newburg Zone (Middle-Upper Silurian) in Ohio,” *The Ohio Journal of Science*,” vol. 91, no. 5, pp. 209-215, 1991.

[9] R.A. Riley with GIS and cartography by J. McDonald, D.R. Martin, “Elevation Contours on the Base of the Deepest Underground Sources of Drinking Water in Ohio,” Ohio Department of Natural Resources, Division of Geological Survey, Map EG-6, 2012.

[10] C. Frederick, M.P. Angle, “Ground Water Pollution Potential of Pike County, Ohio,” Ohio Department of Natural Resources, Division of Water Resources, 2003.

[11] *Standard Guide for Purging Methods for Wells Used for Ground Water Quality Investigations*, ASTM D6452-18, reapproved 2023.

[12] Collection of methods for analyzing trace elements and major cations in solution. EPA 6000 Series.

[13] *Determination of Metals and Trace Elements in Water and Wastes by Inductively Coupled Plasma – Atomic Emissions Spectrometry*, EPA Method 200.7, rev. 4.4, 1994.

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

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

[16] Collection of methods for analyzing specific parameters of water and wastewaters, SM 4500 Series.

[17] *Determination of Ammonia Nitrogen by Semi-Automated Colorimetry*, EPA Method 350.1, rev. 2.0, 1993.

[18] *Nitrogen, Ammonia (Colorimetric, Titrimetric, Potentiometric Distillation Procedure)*, EPA Method 350.2, 1974.

[19] *Standard Test Methods for Total and Dissolved Carbon Dioxide in Water*, ASTM D513-16, 2016.

[20] *Residue, Filterable (Gravimetric, Dried at 180°C)*, EPA Method 160.1, 1971.

[21] *Solids in Water*, SM2540C, 2015.

[22] *Standard Test Methods for Filterable Material (Total Dissolved Solids) and Nonfilterable Matter (Total Suspended Solids) in Water*, ASTM D5907-18.

[23] *Titration Method*, SM 2320B, 2005.

[24] *Standard Test Method for Alkalinity in Brackish Water, Seawater, and Brines*, ASTM D3871-17, 2017.

[25] *pH (Electrometric)*, EPA Method 150.1, 1982.

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

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

[28] *Temperature of Water*, SM 2550B, 2010.

[29] *Conductance (Specific Conductance, umhos at 25°C) by Conductivity Meter*, EPA Method 120.1, 1982.

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

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

[32] *Standard Test Methods for Specific Gravity of Water and Brine*, ASTM D1429-13, 2013.

[33] *Standard Test Method for Density and Relative Density (Specific Gravity) of Viscous Materials by Bingham Pycnometer*, ASTM D1480-21, 2021.

[34] *Standard Test Method for Density, Relative Density, and API Gravity of Liquids by Digital Density Meter*, ASTM D4052-22, 2022.

[35] A.K. Furre, O. Eiken, H. Alnes, J.N. Vevatne, A.F. Kiær, "20 years of monitoring CO_2-injection at Sleipner," *Energy Procedia*, 114, pp. 3916-3926, 2017.

[36] U.S. DOE, "Detection Thresholds and Sensitivities of Geophysical Techniques for CO2 Plume Monitoring," *NRAP Technical Report Series*, NRAP-TRS-I-001-2020; DOE.NETL-2021.2638, 2020.

[37] U.S. DOE, "Monitoring, Verification, and Accounting (MVA) for Geologic Storage Projects," *Best Practice Manual*, DOE/NETL-2017/1847, revised edition, 2017.