5.0 Testing and Monitoring Plan

This chapter describes the testing and monitoring the Alliance will undertake in accordance with 40 CFR 146.89, 146.90, and 146.91 to verify that the Morgan County CO_2 storage site is operating as permitted and is not endangering any USDWs. The Testing and Monitoring Plan described in this chapter is part of the UIC Class VI Permit Application submitted by the Alliance for construction and operation of CO_2 injection wells in Morgan County, Illinois.

This plan describes components of the Monitoring, Verification, and Accounting (MVA) program, which includes hydraulic, geophysical, and geochemical components for characterizing the complex fate and transport processes associated with CO_2 injection. The injection and monitoring wells within the target injection zone will be monitored for the duration of the project to characterize pressure and CO_2 transport response and guide operational and regulatory decision-making. These monitoring results, along with those from a deep early-detection monitoring well installed to just above the primary confining zone, will likely provide the first indication of any unanticipated containment loss. If a containment loss is detected, a modeling evaluation of any observed CO^2 migration above the confining zone would be used to assess the magnitude of containment loss and make bounding predictions regarding the expected impacts on shallower intervals, and ultimately, the potential for adverse impacts on USDW aquifers and other ecological impacts. Comparison of observed and simulated arrival responses at the early-detection well and shallower monitoring locations would continue throughout the life of the project and would be used to calibrate and verify the model, and improve its predictive capability for assessing the long-term environmental impacts of any observed loss of CO_2 containment.

In addition to direct monitoring, the MVA program will also adopt indirect monitoring methodologies for assessing CO_2 fate and transport within the injection zone. Methods will be evaluated and screened throughout the design and initial injection testing phase of the project to identify the most promising monitoring technologies under site-specific conditions. Based on the results of this evaluation, one or more indirect monitoring methods will be selected for implementation. Screening criteria will include 1) data quality; 2) implementability; 3) cost effectiveness, including both capital cost and long-term monitoring costs; and 4) landowner/public impacts (e.g., noise, traffic congestion, property access). An example of factors affecting this screening process is provided by consideration of the electrical resistivity tomography (ERT) technology. Although implementation of ERT will require nonstandard well designs and construction (i.e., the use of non-conductive casing) and thus involve increased capital cost, once it is in place the long-term monitoring cost will be low and the technology will provide continuous real-time results. Two- and three-dimensional seismic methods, which have proved to be an effective monitoring approach at other GS sites, provide another example of screening process considerations. An initial 2D seismic-reflection survey was conducted at the Morgan County site, but the quality of the data obtained from the survey was poor and thus the efficacy of seismic methods for characterization and plume tracking under site conditions was called into question. A reinterpretation of site 2D seismic-reflection data that incorporates recently obtained information on local geologic structure is under way. These results will be used to further assess the effectiveness of seismic methods under site-specific conditions and determine whether they represent a viable monitoring technology for the Morgan County site.

Direct monitoring of the lowermost USDW aquifer is required by the EPA's UIC Class VI GS Rule (75 FR 77230) and is a primary objective of this monitoring program. Additional surface or near-surface-monitoring approaches that may be implemented include shallow groundwater monitoring, soil-gas monitoring, atmospheric monitoring, and ecological monitoring. If implemented, the associated networks of shallow monitoring locations will be designed to provide 1) a thorough assessment of baseline conditions at the site and 2) spatially distributed monitoring locations that can be routinely sampled throughout the life of the project. The need for surface-monitoring approaches will be continually evaluated throughout the design and operational phases of the project, and may be discontinued if deemed unnecessary for the MVA assessment. Given our current conceptual understanding of the subsurface environment, early and appreciable impacts on near-surface environments are not expected, and thus extensive networks of USDW aquifer, surface-water, soil-gas, and atmospheric monitoring stations are not warranted. Any implemented surface-monitoring networks would be optimized to provide good areal coverage while also focusing on areas of higher leak potential (e.g., near the injection wells or other abandoned well locations). If deep early-detection monitoring locations indicate that a primary confining zone containment loss has occurred, a comprehensive near-surface-monitoring program could be implemented to fully assess environmental impacts relative to baseline conditions.

Section 5.1 of this chapter describes the design of the monitoring network, Section 5.2 describes the planned monitoring activities, including the frequencies with which they will be conducted, and Section 5.3 discusses how the monitoring activities described in Section 5.2 will be used to verify effective sequestration and account for all injected CO_2 mass. A brief description of project schedule is presented in Section 5.4 and the data management plan for organizing and storing information collected or generated by the monitoring activities is described in Section 5.5. Section 5.6 describes the criteria for periodic review and updating of this Testing and Monitoring Plan. Finally, Section 5.7 describes the quality assurance program under which the planned testing and monitoring activities will be performed. References for sources cited in the chapter are listed in Section 5.8.

5.1 Conceptual Monitoring Network Design

The monitoring network design was developed based on the current conceptual understanding of the Morgan County CO_2 storage site and was used to guide development of the testing and monitoring approaches described in Section 5.2. Note that this conceptual design will be modified as required based on any additional site-specific characterization data collected at the Morgan County CO_2 storage site, and any significant changes in our conceptual understanding of the site may result in changes to the Testing and Monitoring Plan. The technical approaches described in Section 5.2 should be considered working versions that over time will be updated and modified as required in response to changes in the site conceptual model and/or operational parameters.

Previous CO_2 GS demonstration projects have used a variety of techniques to monitor the injection and migration of CO_2 within the injection zone, and to evaluate the potential for migration of CO_2 through confining zones and to near-surface environments. Techniques used at other sites include both direct (e.g., pressure and aqueous monitoring within and above the injection zone) and indirect measurements (e.g., surface/downhole/cross-borehole geophysical measurements, land surface elevation mapping). During development of the monitoring systems design for the Morgan County storage site, experience gained at other sites was considered, as were previously developed GS guidance documents. Guidance documents that were consulted during development of the project Testing and Monitoring Plan include those published by the EPA (2011) and DOE/National Energy Technology Laboratory (DOE/NETL 2009). The monitoring systems that will be considered for deployment at the Morgan County CO_2 storage site to meet MVA requirements are discussed in detail in Section 5.2.

5.1.1 Environmental Monitoring Considerations

Potential release pathways and the possibility for associated environmental impacts were both considered during development of the monitoring strategy and inform the design basis for the various monitoring system components.

5.1.1.1 Release Pathways

Potential pathways for release of CO_2 from the targeted injection zone include diffuse release across the confining zone; concentrated release through natural faults, fractures, and bedding planes; and release along existing active or abandoned well bores. A detailed discussion of these potential release pathways is provided in Chapter 2.0 (see summary in Section 2.9) and Chapter 3.0 (Section 3.2). A site-specific assessment of potential release pathways identified the following:

- Diffuse release: previous studies and site-specific information indicate a low likelihood of diffuse release from permeation of the primary confining zone.
- Geologic features: A 2D seismic-reflection survey conducted at the Morgan County CO_2 storage site provided no clear indication of major tectonic structures or faults. However, the quality of the seismic survey data was insufficient to rule out the presence of small-scale faults/fracture zones. Morgan County is not located in a seismically active part of the state and has no geologic faults or fracture zones shown on the structural geology map published by the ISGS. In addition, wireline logs obtained from the stratigraphic well showed no indication of significant fracturing within the injection or primary confining zones. A reinterpretation of the 2D seismic-reflection data that incorporates recently obtained information about the local geologic structure is underway. These results will be used to further assess the effectiveness of seismic methods under site-specific conditions and to better understand the presence/absence of localized geologic features of concern. These results will be provided to the EPA.
- Artificial penetrations: The closest preexisting, non-project-related well that penetrates the primary confining zone, and thus provides a potential preferential pathway between the injection zone and shallow USDW aquifers, is located at the Waverly Storage Field approximately 16 mi south-southeast of the Morgan County CO_2 storage site. This location is well outside the project AoR. Within the AoR, three abandoned oil and gas wells were identified that extend to depths of approximately 1,000 to 1,500 ft bgs. These wells do not penetrate the primary or secondary confining zones, but they do represent potential candidate locations for soil-gas monitoring because of their potential for providing a preferential pathway for CO_2 gas transport through shallow shale units (e.g., Maquoketa and New Albany shales). No wells were identified that require corrective action.

5.1.1.2 Potential Environmental Indicators

Migration of injected CO_2 from the injection zone into overlying formations via available (but currently unknown) pathways could result in the following CO_2 phases in overlying aquifers: 1) separate liquid phase CO_2, 2) miscible CO_2 partitioning into existing aqueous phase, and 3) CO_2 gas (i.e., at less than 1,070 psi). CO_2 injection might also result in displacement of hypersaline water from the injection zone that could adversely affect water quality in overlying permeable intervals. If release pathways are present and injected CO_2 migrates into an overlying aquifer, it would introduce increased carbonate concentration, cause some acidity (from the carbonate and/or minor components such as sulfur dioxide [SO_2]), and potentially introduce other trace metals present in the injected CO_2. Consequently, the monitoring program is designed to monitor the CO_2 injection process over the range of relevant locations, phases, and potential secondary chemical by-products that could result from CO_2 migration.

Some typical physical and geochemical indicators that can be used to monitoring CO_2 injection processes occurring within the injection zone include 1) change in the pressure gradients and flow patterns within the injection zone due to the pressurized injection of CO_2, 2) changes in injections zone permeability over time associated with precipitate formation, 3) long-term lateral movement of the CO_2 plume within the injection zone, and 3) minute land surface elevation changes (i.e., upward doming) above the injected CO_2 plume. In the event of a containment loss, partitioning of CO_2 (in and of itself, excluding trace co-contaminants) into overlying permeable zones will have generally minor water-quality impacts, because the Ironton Sandstone and Potosi Dolomite (permeable intervals above the primary confining zone) already have generally poor water quality. However, the potential does exist for decreases in water quality, including 1) increased TDS; 2) increased carbonate, sodium, and chloride concentration; 3) increased trace metals concentrations; and 4) decreased pH. Given that the Ironton Sandstone unit directly overlying the primary confining zone is not potable, these initial water-quality impacts are inconsequential. Secondary (i.e., longer-term) impacts of CO_2/hypersaline fluids migration into an overlying aquifer include 1) carbonate precipitation (calcite, dolomite, and dawsonite), 2) metals mobilization caused by the CO_2 acidification and dissolution of aquifer mineral phases, and 3) changes in aquifer redox state (from reduced to oxic) resulting from coinjecting of dissolved oxygen along with the CO_2, and the associated potential for mobilization of precipitated/reduced metals. Precipitation of carbonates may also decrease permeability in overlying formations, but this is unlikely to be significant (or may be highly localized) because any containment loss is likely to be small in volume relative to the water in an overlying aquifer.

The expected CO_2 injection stream composition is presented in Chapter 4.0, Table 4.1. The CO_2 source is expected to be at least 97 percent pure with the balance of the stream including oxygen, water vapor, and other trace constituents. The injection stream will be continuously monitored at the injection wells for verification and reporting. Although the major component being injected at the Morgan County storage site is CO_2, other minor components may also have some influence on the groundwater geochemistry (i.e., precipitation reactions or may simply be useful as tracers of the injected CO_2.

Experiments designed to assess the relative importance of the above water-quality impacts under site-specific conditions have been initiated and are planned to continue throughout the design phase of the project. However, preliminary bench-scale results, and a detailed discussion of the experimental plan, are beyond the scope of this UIC permit application and will not be included here.

5.1.2 Numerical Modeling

Numerical modeling of the CO_2 injection process will follow the approach described in the EPA guidance for GS modeling (EPA 2011, Section 3.2). Numerical modeling will progress through the following steps: 1) develop site conceptual model, 2) determine the physical processes to be included in the model, 3) implement the numerical model, and 4) execute the simulations. Initial development of the site conceptual model (see Section 3.1.3) is based on available data from the deep Morgan County stratigraphic well installed under this project, along with data from the literature and other wells located in the surrounding area. As additional characterization data are collected, the site conceptual model will be revised and the modeling steps described above will be updated to incorporate new knowledge about the site. The numerical simulations will include multi-fluid and density-dependent flow and transport of dissolved solutes (e.g., water, $scCO_2$, gas-phase CO_2, dissolved CO_2, co-injected tracers, brine), and thermal energy transport where appropriate. The numerical simulator STOMP-CO2 developed by Pacific Northwest National Laboratory (PNNL) will be the primary simulator for modeling multiphase flow conditions (White et al. 2012; White and Oostrom 2006; White and McGrail 2005).

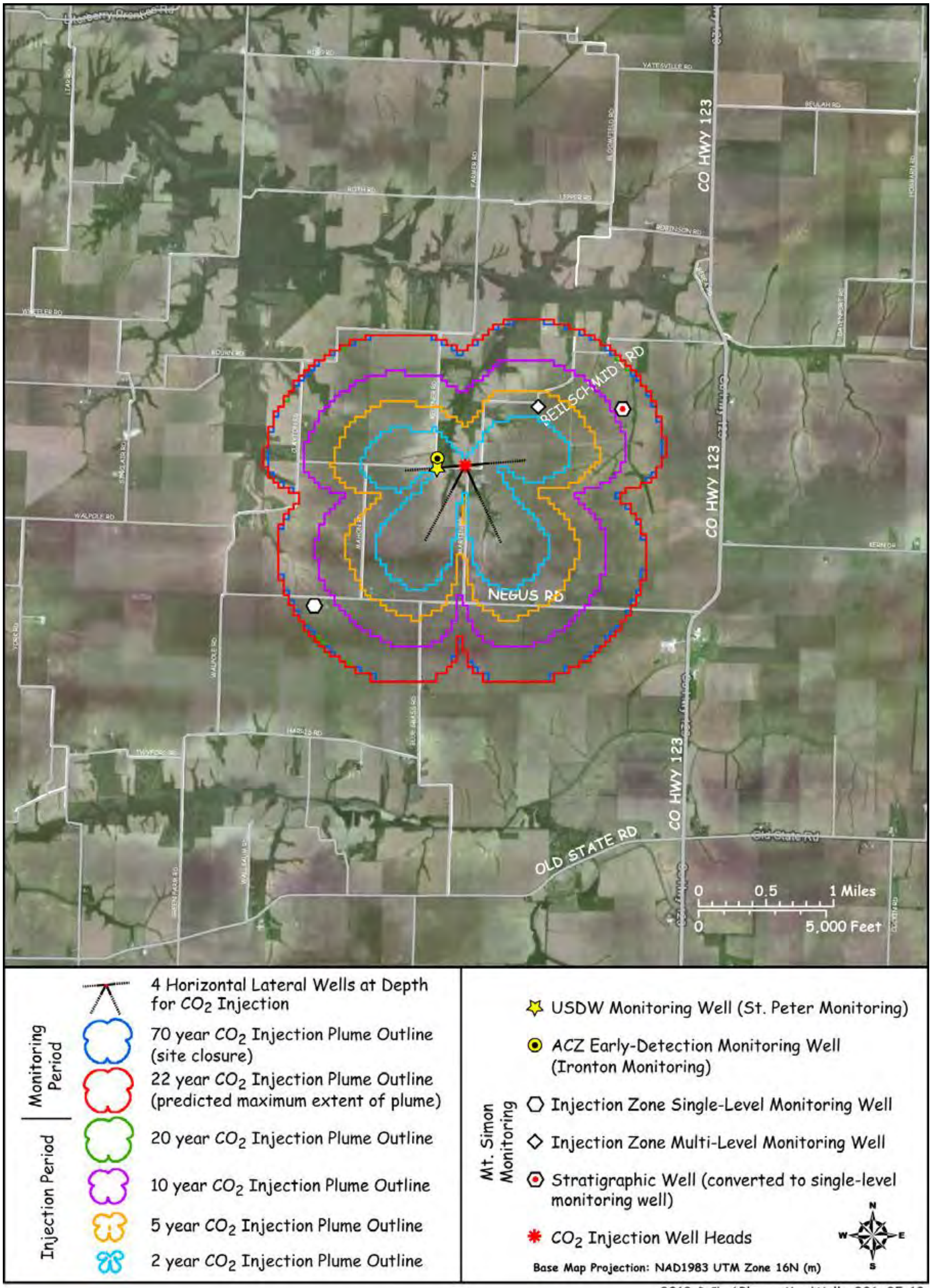
In addition to the reservoir modeling described in Chapter 3.0 that is being performed to satisfy requirements of the UIC permit application, an additional modeling effort focused on evaluation of environmental release scenarios, may be performed. This environmental release model would be developed to support design, operation, and maintenance of the MVA program if significant technical and cost benefit, and/or improved public acceptance would be realized. Results from the reservoir modeling effort (Chapter 3.0) will be used to estimate the spatial extent and distribution of the CO_2 injection volume and the pressure buildup distribution within the reservoir under various operational scenarios, which in turn will be used to guide monitoring systems design (e.g., monitoring and geophysical well spacings, geophysical measurement configurations). The reservoir model will also be used to generate boundary conditions for the lower boundary of the environmental release model. This flow and transport model, which will encompass the overburden materials between the injection zone and ground surface, will be used to predict vertical migration of CO_2 and/or brine under various containment loss scenarios and to assess the potential for impacts on shallow USDW aquifers. Numerical models will be maintained throughout the life of the project and will be routinely updated to support reevaluation of the AoR delineation and any required amendments to this Testing and Monitoring Plan.

5.1.3 Defining the Area of Review

According to EPA guidance (EPA 2011), an AoR is "the region surrounding the GS project where USDWs may be endangered by the injection activity." A detailed discussion of the AoR determination for the Morgan County CO_2 storage site is provided in Chapter 3.0. The resulting AoR is shown in Figure 5.1 as the 22-year CO_2 plume (defined as the area encompassing 99% of the CO_2 mass). The 22-year contour represents the predicted maximum lateral extent of the injected CO_2 volume during the injection and post-closure monitoring periods.

5.1.4 Monitoring Well Network

This section describes the conceptual monitoring well network that will be used to support collection of the various characterization and monitoring measurements needed to track development of the CO_2 plume within the injection zone and identify/quantify any potential release of CO_2 from containment that may occur. The monitoring well locations, shown in the figures below, are representative but approximate and subject to landowner approval. A detailed description of the various components of this monitoring network is provided in Section 5.2. The conceptual monitoring network design (Figure 5.1 and Figure 5.2) is based on the Alliance's current understanding of the site conceptual model and predictive simulations of injected CO_2 fate and transport. A detailed description of the site conceptual model and AoR determination is provided in Chapters 2.0 and 3.0 of this supporting documentation, respectively. Chapter 4.0 of this supporting documentation provides a detailed description of operational parameters (e.g., injection rates, volumes, scheduling, etc.) and well construction details.



2013-DCL-6PlumesMonWells-001_05-10

Figure 5.1. Conceptual Injection and Monitoring Well Network Layout with Predicted CO_2 Lateral Extent over Time

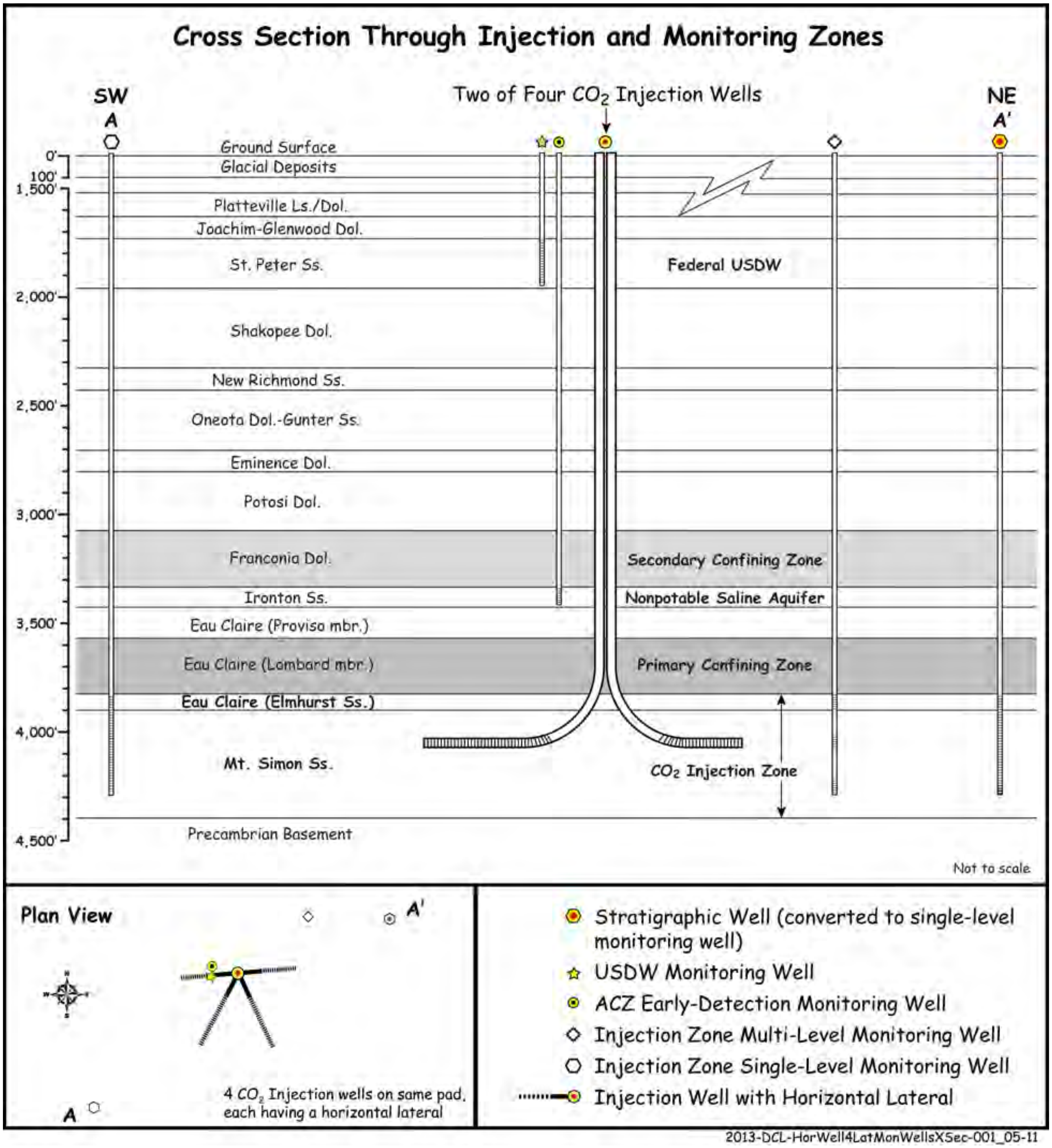


Figure 5.2. Cross-Sectional View of Injection and Monitoring Well Network

The selected monitoring network layout and well designs have been informed by site-specific characterization data collected from the stratigraphic well at the Morgan County CO_2 storage site, and consider structural dip, expected ambient flow conditions, and the potential for heterogeneities or horizontal/vertical anisotropy within the injection zone and overburden materials. The final design may be modified based on ongoing 3D reactive transport modeling that incorporates 1) additional site-specific characterization measurements from the stratigraphic well (e.g., additional hydraulic testing, vertical seismic profiling, etc.), 2) additional characterization data collected during injection well installation, and

3) practical constraints such as land access and the desire to minimize landowner impact. As such, well locations shown in Figure 5.1 could change but only to the extent that they retain their monitoring intent described in the following sections . The location of any wells required to support implementation of indirect monitoring approaches will be determined once candidate technologies have been evaluated and the selection process completed.

5.1.4.1 Injection Zone Monitoring Wells

As indicated in Figure 5.1, well installations within the target injection zone (Mount Simon Sandstone and Elmhurst Sandstone member of the Eau Claire Formation) include four horizontal injection wells and three monitoring wells. Two of the injection zone monitoring wells will be single-level completions located within the predicted lateral extent of the 5- to 25-year CO_2 plumes. The monitoring network will also include one injection zone monitoring well located within the predicted lateral extent of the 2- to 5-year CO_2 plume and ideally within the predicted lateral extent of the 2- to 3-year CO_2 plume. This well may be completed as a multi-level installation, using either 1) a dedicated multi-level monitoring system (e.g., Westbay System) within a single casing string completed with multiple sampling intervals, or 2) a multi-level piezometer installation. Multi-level monitoring is useful for assessing vertical anisotropy during site-specific characterization of the injection zone and for monitoring the vertical distribution of CO_2 within the injection zone during injection operations. All wells extending into the injection zone will be designed and installed to maintain an effective, long-term seal through the overlying primary confining zone. Injection well completion and construction details are discussed in Chapter 4.0 of this supporting documentation.

5.1.4.2 Monitoring Well Installed Immediately Above the Primary Confining Zone

A single above confining zone (ACZ) early-detection monitoring well will be installed within the first permeable interval above the primary confining zone, which most likely will be the Ironton Sandstone unit. The well will be located in the vicinity of the injection well drill pad, within the region of highest pressure buildup. This well might also be used for vertical seismic profiling (VSP) and/or microseismic (MS) monitoring. This multiuse approach will only be implemented if it can be shown that aqueous monitoring or other monitoring related activities will not interfere with the continuous microseismic monitoring at these locations. Construction detail for this well installation is still under development and thus not included in this supporting documentation.

5.1.4.3 Monitoring Well Installed in Lowermost USDW

One of the primary objectives of the monitoring program is to adequately characterize baseline water quality within the lowermost USDW aquifer at the site, including the degree of temporal variability in groundwater quality. These baseline data will be the basis of comparison for measurements collected during operational phases of the project and will be used to assess whether any adverse impacts are occurring as a direct result of CO_2 injection operations. As discussed in Chapter 2.0 (Section 2.6), the lowermost USDW aquifer at the Morgan County site, based on water-quality considerations, resides within the St. Peter Sandstone. A single regulatory compliance well will be installed within this lowermost USDW aquifer, proximal to the ACZ early-detection monitoring well and within the region of highest pressure buildup (Figure 5.1). Construction detail for this well installation is still under development and thus not included in this supporting documentation.

5.2 Monitoring Activities

The primary objective of the MVA program is to track the lateral extent of CO_2 within the target reservoir and determine whether it is effectively contained within the injection zone. Other monitoring objectives include characterizing any geochemical or geomechanical changes that occur within the injection zone and overlying confining zone and monitoring any change in land surface elevation associated with CO_2 injection. If the overlying confining zone (i.e., upper members of the Eau Clair Formation) is found to not act as a competent caprock material, another primary objective of the monitoring program will be to quantify the magnitude of the containment loss and assess the potential for it to adversely affect water quality in USDW aquifers.

5.2.1 Monitoring Program Summary

This section provides a brief overview of the MVA program. Details for the various components of this monitoring program are discussed in the sections below.

5.2.1.1 General Approach

The proposed monitoring program includes hydraulic, geophysical, and geochemical components for characterizing the complex fate and transport processes of a CO_2 injection. Injection into the Mount Simon Sandstone, which contains hypersaline waters at pressures greater than the critical pressure for maintaining CO_2 in the supercritical state, will effectively maintain the supercritical fluid conditions. Supercritical CO_2 is considered to be immiscible with water due to its hydrophobic nature, although some CO_2 will dissolve in water along the interface between the $scCO_2$ plume and the surrounding reservoir fluids. If any loss of containment from the confining zone occurs and the injected CO_2 is transported to shallower depths, where the hydrostatic pressure decreases below the critical value (1,070 psi at 31°C), the $scCO_2$ will change to the gas phase. Gas-phase CO_2 will partially dissolve into the water solution, and the remaining portion will exist as entrapped gas. Because of these multiple liquid/gas phases, leak detection above the primary confining zone involves monitoring changes in the aqueous phase (predominantly pH, carbonate, and trace metal changes in water), the $scCO_2$ phase, and the gas phase (CO_2 and other gases).

Carbon dioxide and other liquids/gases can potentially migrate through the primary confining zone and overlying formations by 1) slow permeation through porous intervals, 2) increased transport through existing or induced fractures in the formations, and 3) leakage along the injection well or other abandoned wells in the vicinity. Given the complexity of this system, a comprehensive monitoring program is needed to assess all potential migration pathways. Based on an evaluation of both regional and site-specific information (see Sections 2.1.2.3 and 2.1.3.2), migration of CO_2 and brine through the overlying primary confining zone is thought to be unlikely. In addition, simulation results from a previous study indicated <1 m of CO_2 transport into a shale after 100 years of CO_2 injection (Person et al. 2010). However, the integrity of this confining zone material will remain uncertain until site-specific characterization is completed. Natural and pressure-induced fractures in the Eau Claire Formation and/or limited thickness of the confining intervals could increase the likelihood of containment loss. There are no preexisting (i.e., not project-related) deep boreholes that penetrate the Mount Simon Sandstone in the immediate vicinity of the proposed injection well locations; the closest well is approximately 16 mi away, so preferential vertical migration related to project-installed injection and monitoring wells will be one of the most important pathways to monitor.

As discussed in the introduction to this chapter, the monitoring program will adopt 1) both direct and indirect monitoring methodologies for assessing CO_2 fate and transport within the injection zone, 2) early-detection monitoring immediately above the primary confining zone, 3) direct monitoring of the lowermost USDW aquifer, and 4) other near-surface-monitoring technologies (as needed to meet project or regulatory requirements), including shallow groundwater, soil-gas, atmospheric, and ecological monitoring. A summary of testing and monitoring activities is provided in Table 5.1 and Table 5.2. Table 5.1 specifies technologies that are a GS Rule requirement and/or considered by the Alliance to be critical monitoring activities. Table 5.2 includes additional indirect geophysical monitoring techniques and surface leak-detection monitoring methodologies that will be evaluated by the project and may or may not be implemented in the monitoring program. Methods will be evaluated and screened throughout the design and initial injection testing phase of the project to identify the most promising monitoring technologies under site-specific conditions. At a minimum, at least one indirect geophysical monitoring technique will be carried forward through the operational phases of the project.

Planned monitoring frequencies for each of these monitoring methodologies throughout the life of the project (i.e., for those selected for implementation) are provided in Table 5.3. As indicated, there will be five general phases of aqueous monitoring: baseline monitoring, DOE active injection monitoring, commercial injection monitoring, and commercial post-injection monitoring.

5.2.1.2 Monitoring Considerations and Supporting Studies

Injection of CO_2 above supercritical pressure (1,070 psi) into the targeted injection zone will result in both lateral advection and upward migration of the CO_2 plume. Upward migration results from buoyancy effects associated with $scCO_2$, which has a significantly lower density (0.47 to 0.83 g/cm^3 depending on pressure and temperature conditions) than the reservoir fluids. The $scCO_2$ will have limited solubility into water at the advection front, so near the injection well it should displace essentially all water and "dry out" the pore space. Emplacement of the CO_2 plume results in multiple CO_2 phases (liquid, gas, solid) that include 1) $scCO_2$ liquid (hydrophobic, will incorporate and mobilize organic phases, if present), 2) predominantly aqueous phase that incorporates some carbonate, 3) carbonate precipitates, and 4) CO_2 gas phase (in formations where pressure is $<$1,070 psi) and other minor gas phases present (i.e., oxygen, nitrogen, argon).

The complex geochemical changes that can occur within the injection zone have been partially characterized for the Mount Simon Sandstone in previous laboratory studies, but not under site-specific conditions or in other potential aquifer zones present in the overburden materials. To better understand these processes, a series of laboratory experiments will be performed using site-specific injection zone cores and representative $scCO_2$ fluids to evaluate geochemical, microbial, and physical changes that may occur within the injection zone as a result of CO_2 storage. Due to the spatial and temporal evolution of potential geochemical changes, trace metals in the CO_2 injection stream and those mobilized from aquifer solids can be of concern, so they are included in this monitoring plan.

Table 5.1. Summary of Planned Testing and Monitoring Activities

Monitoring Category	Monitoring Method	Description
CO_2 Injection Stream Monitoring	Sampling and analysis	Monitoring of the chemical and physical characteristics of the CO_2 injection stream.
CO_2 Injection Process Monitoring	Continuous monitoring of injection process	Continuous monitoring of injection mass flow rate, pressure, and temperature, annular pressure, and fluid volume.
Well Mechanical Integrity Testing (one or more methods selected for implementation)	Oxygen-activation tracer Logging	Geophysical tracer logging technique that uses a pulsed-neutron tool to quantify flow of water in or around a borehole.
	Radioactive tracer logging	A radioactive tracer survey (RTS) that uses a wireline tool to detect the location(s) (e.g., perforations, leaks through casing) where the injected tracer exits from or migrates along the well bore.
	Temperature logging	Identifies injection-related fluids that have moved along channels adjacent to the well bore.
	Pressure fall-off testing	A pressure transient test that involves shutting in the injection well after a period of prolonged injection and measuring pressure decline.
Corrosion Monitoring of Well Materials	Corrosion coupon method	Coupons consisting of the same material as the casing and tubing will be placed in the CO_2 injection line and periodically removed for corrosion inspection.
	Wireline monitoring of casing and tubing	Ultrasonic, electromagnetic, and/or mechanical logging tools used to evaluate the condition of the well casing and the CO_2 injection tubing.
	Cement-bond logging	Verifies the integrity of the cement bond to the well casing and formation in the presence of CO_2 and injection zone brine.
Groundwater Quality and Geochemistry Monitoring	Early leak-detection Monitoring	Fluid sampling and field parameter monitoring for early leak detection within the deepest permeable zone (e.g., Ironton Sandstone) located above the primary confining zone.
	USDW aquifer monitoring	Fluid sampling and field parameter monitoring for leak detection and assessment of water-quality impacts to the lowermost USDW aquifer (St. Peter Sandstone).
Injection Zone Monitoring	Single-level monitoring wells	Fluid sampling and field parameter monitoring for assessment of CO_2 fate and transport and leak detection.
	Multi-level monitoring wells	Fluid sampling and field parameter monitoring for assessment of CO_2 fate and transport and leak detection, injection zone heterogeneity, and anisotropy.
Indirect Geophysical Monitoring Techniques	Multiple technologies tested for efficacy and cost effectiveness, one or more selected for deployment	See Table 5.2 for details on technologies under consideration.

Table 5.2. Additional Monitoring Activities Under Consideration

Monitoring Category	Monitoring Method	Description
Indirect Geophysical Monitoring Techniques (surface)	Integrated deformation monitoring	Uses a combination of tools (e.g., satellite Interferometric Synthetic Aperture Radar, tiltmeter, and global positioning system) to measure the magnitude and geographical extent of deformation associated with CO_2 injection.
	3D multi-component surface seismic monitoring	Provides the basic framework for building the conceptual reservoir model and tracking subsurface distribution and migration of CO_2.
	Magnetotelluric (MT) sounding	Measures changes in electromagnetic field resulting from variations in electrical properties of CO_2 and formation fluids.
	Time-lapse gravity	Used to measure variations in density in the subsurface due to CO_2 injection.
Indirect Geophysical Monitoring Techniques (downhole)	Vertical seismic profile(ing) (VSP)	Downhole seismic survey performed in a well bore with multi-component processing. Provides high-resolution seismic data for identifying distribution and migration of CO_2. Can be used to calibrate 2D and 3D seismic-reflection surveys.
	Cross-well seismic imaging	Eliminates near-surface noise and provides high-resolution imaging of plume migration by placing both seismic sources and receivers in well bores.
	Passive seismic monitoring (microseismicity)	Observed microseismic activity induced by CO_2 injection. Provides accurate location and focal mechanism of seismic events allowing real-time monitoring of reservoir and caprock integrity during injection and addresses induced seismicity concerns.
	Real-time ERT	Permanent downhole installation that measures the resistivity changes caused by CO_2 injection and migration in geological reservoirs.
	Real-time distributed temperature sensing (DTS)	Fiber-optic sensor cables permanently installed behind the well casing of injection and/or monitoring wells to measure real-time temperatures with high temporal and spatial resolution.
Indirect Geophysical Monitoring Techniques (wireline logging)	Pulsed-neutron capture	Detects and helps quantify CO_2 saturations.
	Sonic (acoustic) logging	Determines location and azimuth of strike of natural and induced fractures, both in the reservoir and caprock, and changes in acoustic velocity due to changes in the CO_2 saturation.
	Gamma-ray logging	Detects changes in uranium, thorium, and radioactive potassium that can be related to rock properties and/or fluid movement behind the casing or in the reservoir.

Table 5.2. (contd)

Monitoring Category	Monitoring Method	Description
Surficial Aquifer Monitoring	Groundwater monitoring in local landowner wells	Fluid sampling and field parameter monitoring for assessment of surficial aquifer water quality
Soil-Gas Monitoring	Shallow soil-gas monitoring	Soil-gas collector chambers and/or standard soil-gas sampling points will be used to monitor the concentration of CO_2 and other noncondensable gases (e.g., N, O) in shallow soils.
	Tracer and isotopic signature monitoring	Soil-gas sampling for carbon and oxygen isotopic signature and/or tracer compounds injected along with the CO_2 to improve leak-detection capabilities.
Atmospheric Monitoring	Fixed-point CO_2 and tracer monitoring	Continuous CO_2 measurement at fixed location, with routine sampling for CO_2 and tracer gas concentrations. Tracer gases will provide improved leak-detection capability.
	Mobile CO_2 and tracer monitoring	Periodic measurements of CO_2 and tracer gas using a mobile, real-time instrument, near injection/monitoring wells and along transects spanning the AoR.
	Weather Station (at two fixed-point locations)	Measurements of air temperature, relative humidity, precipitation, barometric pressure, solar radiation, soil moisture, and soil temperature.
Ecological Monitoring	Baseline ecological survey	Pre-operational monitoring and characterization to establish baseline conditions for comparisons with operational monitoring results.
	Continuous surface-water monitoring	Continuous measurement of pH, temperature, electrical conductivity, and dissolved oxygen content of nearby surface waters.
	Remotely sensed data for vegetation condition assessment	Satellite imagery used to characterize vegetation conditions and detect subtle changes in normal plant growth processes and relative vegetation stress.

Table 5.3. Monitoring Frequencies by Method and Project Phase for both Planned and Considered Monitoring Activities

Monitoring Category	Monitoring Method	Baseline 3 yr	DOE Active Injection (startup) ~3 yr	DOE Active Injection ~2 yr	Commercial Injection ~15 yr	Post Injection 50 yr
Monitoring Plan Update	NA	As required	As Required	As Required	As Required	NA
CO_2 Injection Stream Monitoring	Grab sampling and analysis	Up to 6 events during commissioning	Quarterly	Quarterly	Quarterly	NA
CO_2 Injection Process Monitoring	Continuous monitoring of injection process (injection rate, pressure, and temperature; annulus pressure and volume)	NA	Continuous	Continuous	Continuous	NA
Well Mechanical Integrity Testing	Oxygen activation, radioactive tracer, and/or temperature logging	Once after well completion	Annual	Annual	Annual	NA (wells plugged)
	Injection well pressure fall-off testing	NA	Every 5 yr	Every 5 yr	Every 5 yr	NA
Corrosion Monitoring of Well Materials	Corrosion coupon monitoring	NA	Quarterly	Quarterly	Quarterly	NA
	Wireline monitoring of casing and/or tubing corrosion and cement	Once after well completion	During well workovers	During well workovers	During well workovers	NA
Groundwater Quality and Geochemistry Monitoring	Early leak-detection monitoring in above confinement zone monitoring wells	3 events	Quarterly	Semi-Annual	Annual	Every 5 yr
	USDW aquifer monitoring (continuous parameter monitoring, aqueous sample collection as indicated)	1 yr continuous monitoring, 3 sampling events	Quarterly	Annual	Annual	Every 5 yr
Injection Zone Monitoring	Single-level monitoring wells	3 events	Annual	Annual	Every 2 yr	Every 5 yr
	Multi-level monitoring wells	3 events	Quarterly	Semi-Annual	Annual	Every 5 yr
Indirect Geophysical Monitoring Techniques (surface)	Integrated deformation monitoring	2 yr min	Continuous	Continuous	Continuous	Continuous
	3D multi-component surface seismic monitoring	Once	NA	Once	Every 5 yr	NA
	Magnetotelluric (MT) sounding	3 events	Once	Once	Every 5 yr	Every 5 yr
	Time-lapse gravity	Once	Semi-Annual	Semi-Annual	Semi-Annual	Every 5 yr

Table 5.3. (contd)

Monitoring Category	Monitoring Method	Baseline 3 yr	DOE Active Injection (startup) ~3 yr	DOE Active Injection ~2 yr	Commercial Injection ~15 yr	Post Injection 50 yr
Indirect Geophysical Monitoring Techniques (downhole)	Vertical seismic profile(ing) (VSP)	Once	Once	Once	Every 5 yr	Every 10 yr
	Cross-well seismic imaging	Once	Once	Once	Every 5 yr	Every 10 yr
	Passive seismic monitoring (microseismicity)	1 yr min	Continuous	Continuous	Continuous	Continuous
	ERT	1 yr min	Continuous	Continuous	Continuous	Continuous
	Real-time distributed temperature sensing (DTS)	1 yr min	Continuous	Continuous	Continuous	Continuous
Indirect Geophysical Monitoring Techniques (wireline logging)	Pulsed-neutron capture, sonic (acoustic) logging, and gamma-ray logging	Once after well completion	Annual	Annual	Annual	NA
Surficial Aquifer Monitoring	Continuous parameter monitoring in 1 project-installed well, aqueous sample collection as indicated	1 yr continuous monitoring, 3 sampling events	Quarterly	Annual	Annual	Every 5 yr
Soil-Gas Monitoring	Samples collected for CO_2, other noncondensable gases and tracers	4 events	Quarterly	Annual	Annual to every 5 yr	Every 5 yr
Atmospheric Monitoring	Continuous CO_2 monitoring, tracer sampling and analysis	1-yr baseline monitoring	Quarterly	Semi-Annual	Annual to every 5 yr	Every 5 yr
Ecological Monitoring	Eco survey for baseline, continuous surface-water monitoring, remote sensing of vegetation conditions as indicated	Eco survey once, 1 yr baseline monitoring,	Annual	Annual	Annual to every 5 yr	Every 5 yr

To better understand the impacts that increased CO_2 concentrations might have on the USDW aquifer, and the resulting acidification that mineral-phase dissolution (and possible change in redox geochemistry) has on the mobilization of trace metals, a series of bench-scale laboratory studies will be performed using site-specific USDW aquifer sediments. These studies will evaluate the changes in aquifer geochemistry and water quality that would be expected to occur at various levels of CO_2 intrusion.

5.2.1.3 Tracer and Isotopic Monitoring

Previous studies have used two different classes of tracers (hydrophobic or "water-fearing" and hydrophilic or "water-loving") that have greater sensitivity and significantly lower detection limits compared with changes in major ion geochemistry or isotopic tracers. These compounds are highly resistant to natural breakdown, so they are persistent in the environment, even under extreme temperature and pressure. One class of hydrophobic tracers, which tend to stay in the $scCO_2$ phase or partition into oil or the gaseous phase, is generally referred to as perfluorinated tracers (PFTs). Three PFTs commonly used in groundwater and reservoir investigations include perfluoro-1,2-dimethylcyclohexane (PDCH), perfluorotrimethyl-cyclohexane (PTCH), and perfluorodimethylcyclobutane (PDCB). Each of these tracers has been previously injected with CO_2 (Wells et al. 2007; Eastoe et al. 2003). These tracers also can be monitored near the land surface to aid in leak-detection monitoring. Use of these types of tracers can result in early detection of the PFT in a shallow aquifer or at land surface (Wells et al. 2007) if that gas phase travels faster than the CO_2, as noted in previous studies (Dietz 1986; Spangler et al. 2009). However, if intervals within the overburden materials contain significant quantities of organic matter, the PFT may partition into that phase and never be transported to shallower monitoring depths. This potential scenario demonstrates the utility of including a hydrophilic component in the tracer suite, which provides an additional measure of leak-detection capability in deeper monitoring intervals.

There are several examples of hydrophilic tracers that partition into the aqueous phase. Naphthalene sulfonate tracers used in previous studies (Rose et al. 2001) include 2-naphthalene sulfonate, 2,7-naphthalene sulfonate, and 1,3,6-naphthalene trisulfonate. Fluorinated benzoic acids that have been used previously include pentafluorobenzoic acid (PFBA), 2,6-difluorobenzoic acid, and 2,3-difluorobenzoic acid (Flury and Wai 2003; Stetzenbach and Farnham 1995).

Direct measurement of CO_2 for leak detection, either in the dissolved or gaseous phase, can be difficult to separate from other carbonate sources in the overlying aquifers or soil zone. Measurement of $^{13/12}C$ isotopic change in the carbonate (or CO_2 soil-gas) has significantly lower detection limits, because the isotopic change is essentially a tracer. In one study, CO_2 gas with a different isotopic $^{13/12}C$ ratio was emitted into the air, and laser measurements in real time were used (Steele et al. 2008). This study demonstrated the effectiveness of isotopic $^{13/12}C$ measurements for characterizing soil-gas composition. Isotopic measurements of $^{13/12}C$ (and $^{18/16}O$ in water) in the past were expensive measurements, requiring a prep line and mass spectrometry. Newly developed off-axis laser absorption spectroscopy has the potential to reduce this cost considerably due to rapid, automated sample analysis on a relatively inexpensive instrument. ^{14}C has also been shown to be a powerful tool for distinguishing between modern biogenic sources of CO_2 (containing ^{14}C) and CO_2 derived from fossil fuel sources (^{14}C has decayed over time). Because injected CO_2 would be expected to be depleted in ^{14}C, this isotopic signature provides another useful tracer that can be used to discriminate between CO_2 released from the injection zone and that naturally present in the near-surface environment.

5.2.2 Groundwater Quality and Geochemistry Monitoring

Direct monitoring of aqueous chemistry and related field parameters will be used to identify and quantify any potential impacts on USDW aquifers from a release of hypersaline waters and/or CO_2 from the injection zone. Monitoring locations will include immediately above the primary confining zone for early leak-detection (i.e., ACZ monitoring wells) and USDW aquifer monitoring.

5.2.2.1 ACZ Early-Detection Monitoring

Direct monitoring of pressure and aqueous chemistry will be used to identify and quantify any potential release of injection zone fluids and/or CO_2 resulting from a loss of containment.

Objectives

Monitoring groundwater in one or more zones between the confining zone(s) overlying the injection zone and the USDW aquifers is required by 40 CFR 146.90 (d). The purpose of such monitoring is to detect CO_2 migration out of the injection zone before it can result in any impacts on USDW aquifer water quality.

Monitoring Approach

Candidate ACZ monitoring intervals that could be used for early leak detection of CO_2 from the injection zone, and thus protect the lowermost USDW from potential water-quality impacts, include permeable units within the upper Eau Claire unit and the Ironton Sandstone (see Figure 5.2). Information from the stratigraphic well at the Morgan County site indicates the Ironton Sandstone unit, which is located immediately above the primary confining zone and should be a viable monitoring interval, will likely provide the best early-detection monitoring capability. One ACZ, early-leak-detection monitoring well will be installed in the vicinity of the injection well pad (Figure 5.1). This well will be perforated in the Ironton Sandstone and completed to facilitate continuous field parameter monitoring and periodic aqueous sampling. This well may also be used to support VSP and passive seismic monitoring, and may be constructed using non-conductive casing so that an array of electrical resistivity electrodes attached to the outside of the casing can be used to provide a real-time, early-detection capability.

Pressure and aqueous monitoring requirements for the early-detection monitoring well, including the general monitoring approach, the list of target analytes, and the analytical and quality assurance requirements, are specified in Section 5.2.2.3, Sampling and Analysis. The planned monitoring frequencies during the various phases of the project are listed in Table 5.3. Once CO_2 injection begins, aqueous monitoring in the early-detection well will be conducted on a regular basis to monitor for potential upward migration of CO_2 out of the targeted injection zone. Additional interim sampling will be conducted if CO_2 containment loss is suspected based on pressure data from the well or other evidence, such as geophysical measurements or other aqueous monitoring results. Post-injection monitoring will nominally extend over a 50-year period, or as required to demonstrate that the injected CO_2 poses no threat to the USDW aquifers (see discussion in Section 7.2). Monitoring of the deep, ACZ early-leak-detection monitoring well for pressure, temperature, electrical conductivity, and aqueous chemistry will be conducted throughout the post-injection monitoring period to support this evaluation. Pressure and electrical conductivity (if ERT is implemented) will be continuously monitored and aqueous samples will be collected on a routine basis.

5.2.2.2 USDW Aquifer Monitoring

Direct monitoring of aqueous chemistry and related field parameters will be used to identify and quantify any potential impacts on USDW aquifers resulting from injection zone containment loss. Given the depth of the targeted injection interval (~4,000 ft bgs), the expected integrity of the overlying confining unit, the presence of the secondary confining units at shallower depths (e.g., the Franconia Dolomite unit), and the lack of any known preferential pathways between the injection zone and USDW aquifers (see Section 5.1.1.1 and Section 3.2.1), the likelihood of CO_2 coming into direct contact with the lowermost USDW aquifer (St. Peter Sandstone, see Figure 5.2), and the associated impacts on water quality, are relatively low. In addition, if a significant breach in the primary confining zone occurred during injection operations, ACZ early-leak-detection monitoring in the Ironton Sandstone should identify the leak and allow for the implementation of mitigation strategies well before any impacts on the overlying USDW aquifers can occur. However, to ensure that the local drinking water supply is adequately protected, a comprehensive USDW monitoring program will be instituted.

Objectives

Monitoring groundwater quality in USDW aquifers is required by 40 CFR 146.90. The intended purpose of this type of monitoring is to detect and quantify any potential impacts of CO_2 containment loss on the water quality of local drinking water aquifers.

Monitoring Approach

As discussed in Chapter 2.0 (Section 2.6.3.1), the lowermost USDW aquifer at the Morgan County site, based on water-quality considerations, resides within the St. Peter Formation. A single regulatory compliance well will be installed within this lowermost USDW aquifer (Figure 5.1 and Figure 5.2). In addition, the shallow surficial aquifer residing within the near-surface glacial deposits will be monitored using one project-installed groundwater monitoring well and a network of approximately 10 local landowner wells. Shallow USDW monitoring will be performed to directly assess groundwater quality at current USDW user locations, which reside exclusively within the shallow semiconsolidated glacial sediments beneath the study area and in surrounding communities.

A general description of this surficial USDW monitoring network and the results from an initial groundwater sampling campaign conducted by ISGS to support characterization of local-scale USDW water quality, is included in Chapter 2.0 (Section 2.6.1). A literature search and evaluation conducted by the ISGS (ISGS in prep) indicate that the upper Pennsylvanian bedrock aquifer is a potentially potable source of drinking water in the region. However, within the immediate vicinity of the Morgan County storage site (and anticipated AoR extent) usage is essentially precluded by 1) decreasing water quality with depth and 2) the difficulty associated with finding geologic material that has enough primary or secondary porosity to generate a well of sufficient yield to act as an economically viable source of drinking water. In addition, current residential/farm usage in the vicinity of the site is limited to wells completed within the shallow Quaternary, glacially derived sediments that compose the surficial aquifer system. All of the smaller towns and communities in the vicinity of the proposed CO_2 injection site obtain water supplies from surface-water sources, sometimes supplemented with shallow groundwater withdrawn from localized more-permeable lenses within the shallow Quaternary sediments. For these reasons, the surficial aquifer system is considered a USDW of interest at the Morgan County storage site, even though it is not the lowermost USDW aquifer.

Monitoring data will be continuously evaluated throughout the active injection phase, and if specific analytes are found to be of little benefit, they will be removed from the analyte list. The post-injection monitoring period will nominally extend over a 50-year period, or as required to demonstrate that the injected CO_2 does not pose a threat to any USDW aquifers. In addition to aqueous sample collection, continuous monitoring of pressure (water level) and other water-quality parameters (specific conductance and pH) will be conducted using dedicated downhole electrodes. Instrumentation will be installed to record these parameters using multiple submersible downhole sensors, all connected to a single above-ground automated data-logging system.

5.2.2.3 Sampling and Analysis

Specific field sampling protocols will be described in a project-specific sampling plan to be developed prior to initiation of field test operations, once the test design has been finalized. The work will comply with applicable EPA regulatory procedures and relevant American Society for Testing and Material, ISGS, and other procedural standards applicable for groundwater sampling and analysis. All sampling and analytical measurements will be performed in accordance with project quality assurance requirements (see Section 5.8), samples will be tracked using appropriately formatted chain-of-custody forms, and analytical results will be managed in accordance with a project-specific data management plan (see Section 5.6). Investigation-derived waste will be handled in accordance with site requirements.

During all groundwater sampling, field parameters (pH, specific conductance, and temperature) will be monitored for stability and used as an indicator of adequate well purging (i.e., parameter stabilization provides indication that a representative sample has been obtained). Calibration of field probes will follow the manufacturer's instructions using standard calibration solutions. A comprehensive list of target analytes under consideration and groundwater sample collection requirements is provided in Table 5.4. The relative benefit (and cost) of each analytical measurement will be evaluated throughout the design and initial injection testing phase of the project to identify the analytes best suited to meeting project monitoring objectives under site-specific conditions. If some analytical measurements are shown to be of limited use and/or cost prohibitive, they will be removed from the analyte list. All analyses will be performed in accordance with the analytical requirements listed in Table 5.5. Additional analytes may be included for the shallow USDW based on landowner requests (e.g., coliform bacteria). If implemented, monitoring for tracers will follow standard aqueous sampling protocols for the naphthalene sulfonate tracer, but a pressurized sample for the PFT tracer will be required because the PFT will be partitioned into the gas phase.

Table 5.4. Aqueous Sampling Requirements

Parameter	Monitoring Phase	Volume/ Container	Preservation	Holding Time
Major Cations: Al, Ba, Ca, Fe, K, Mg, Mn, Na, Si,	All phases	20-mL plastic vial	Filtered (0.45 µm), HNO_3 to pH <2	60 days
Trace Metals: Sb, As, Ba, Cd, Cr, Cu, Pb, Hg, Se, Tl	All phases	20-mL plastic vial	Filtered (0.45 µm), HNO_3 to pH <2	60 days
Anions: Cl^-, Br^-, F^-, SO_4^{2-}, NO_3^-,	All phases	20-mL plastic vial	Cool 4°C	45 days
Gravimetric Total Dissolved Solids (TDS), compare to TDS by calculation from major ions	All phases	250-mL plastic vial	Filtered (0.45 µm), no preservation Cool 4°C	
Water Density	Baseline, periodic during injection	100 mL plastic vial	Filtered (0.45 µm), no preservation Cool 4°C	60 days
Alkalinity	All phases	100 mL HDPE	Filtered (0.45 µm) Cool 4°C	5 days
Dissolved Inorganic Carbon (DIC)	All phases	20-mL plastic vial	Cool 4°C	45 days
Total Organic Carbon (TOC)	All phases	40 mL glass	unfiltered	14 days
Carbon Isotopes (^{14}C, $^{13/12}C$)	Baseline, other phases as indicated	5-L HDPE	pH >6	14 days
Water Isotopes ($^{2/1}H$, $^{18/16}O$)	Baseline only	20-mL glass vial	Cool 4°C	45 days
Radon (^{222}Rn)	All phases	1.25-L PETE	Pre-concentrate into 20-mL scintillation cocktail. Maintain groundwater temperature prior to pre-concentration	1 day
Naphthalene Sulfonate or Fluorinated Benzoic Acid Tracers (aqueous phase)	No baseline, all operational phases	500 mL HDPE	Filtered (0.45 µm), no preservation	60 days
Perfluorocarbon Tracer (PFT) ($scCO_2$ or gas phase)	No baseline, all operational phases	500 mL glass	unfiltered, Cool 4°C	60 days
pH	Monitored during each sampling event	Field parameter	None	<1 h
Specific Conductance	Monitored during each sampling event	Field parameter	None	<1 h
Temperature	Monitored during each sampling event	Field parameter	None	<1 h

HDPE = high-density polyethylene; PETE = polyethylene terephthalate.

Table 5.5. Analytical Requirements

Parameter	Analysis Method	Detection Limit or (Range)	Typical Precision/ Accuracy	QC Requirements
Major Cations: Al, Ba, Ca, Fe, K, Mg, Mn, Na, Si,	ICP-OES, PNNL-AGG-ICP-AES (similar to EPA Method 6010B)	0.1 to 1 mg/L (analyte dependent)	±10%	Daily calibration; blanks and duplicates and matrix spikes at 10% level per batch of 20
Trace Metals: Sb, As, Ba, Cd, Cr, Cu, Pb, Hg, Se, Tl	ICP-MS, PNNL-AGG-415 (similar to EPA Method 6020)	1 µg/L for trace elements	±10%	Daily calibration; blanks and duplicates and matrix spikes at 10% level per batch of 20
Anions: Cl^-, Br^-, F^-, SO_4^{2-}, NO_3^-, CO_3^{2-}	Ion Chromatography, AGG-IC-001 (based on EPA Method 300.0A)		±15%	Daily calibration; blanks and duplicates at 10% level per batch of 20
TDS	Gravimetric Method Standard Methods 2540C	12 mg/L	± 5%	Balance calibration, triplicate samples
Water Density	Standard Methods 227	0.0001 g/mL	±0.0`%	Triplicate measurements
Alkalinity	Titration, standard methods 102	4 mg/L	±3 mg/L	Triplicate titrations
Dissolved Inorganic Carbon (DIC)	Carbon analyzer, phosphoric acid digestion of DIC	0.002%	±10%	Triplicate analyses, daily calibration
Total Organic Carbon (TOC)	Carbon analyzer; total carbon by 900°C pyrolysis minus DIC = TOC	0.002%	±10%	Triplicate analyses, daily calibration
Carbon Isotopes ($^{14/12}C$, $^{13/12}C$)	Accelerator MS	10^{-15}	±4‰ for ^{14}C; ±0.2‰ for ^{13}C;	Triplicate analyses
Water Isotopes ($^2H/^1H$, $^{18/16}O$)	Water equilibration coupled with IRMS ; Alternatively, consider WS-CRDS	10^{-9}	IRMS: ±1.0‰ for ^2H; ±0.15‰ for ^{18}O; WS-CRDS: ±0.10‰ for ^2H; ±0.025‰ for ^{18}O	Triplicate analyses
Radon (^{222}Rn)	Liquid scintillation after pre-concentration	5 mBq/L	±10%	Triplicate analyses
Naphthalene Sulfonate **or** Benzoic Acid Tracer (aqueous phase)	Liquid chromatography-mass spectrometry (LC-MS) **or** gas chromatography with electron capture detector (ECD)	5 parts per trillion (5×10^{12}) **or** 10 parts per quadrillion (10×10^{15})	Varies with conc., ±30% at detection limit	Duplicates 10% of samples, significant number of blanks for cross-contamination
Perfluorocarbon Tracer (PFT) ($scCO_2$ or gas phase)	gas chromatography with electron capture detector (ECD)	10 parts per quadrillion (10×10^{15})	varies with conc., ±30% at detection limit	duplicates 10% of samples, significant number of blanks for cross-contamination

Table 5.5. (contd)

Parameter	Analysis Method	Detection Limit or (Range)	Typical Precision/ Accuracy	QC Requirements
pH	pH electrode	2 to 12 pH units	±0.2 pH unit For indication only	User calibrate, follow manufacturer recommendations
Specific conductance	Electrode	0 to 100 mS/cm	±1% of reading For indication only	User calibrate, follow manufacturer recommendations
Temperature	Thermocouple	5 to 50°C	±0.2°C For indication only	Factory calibration

ICP = inductively coupled plasma; IRMS = isotope ratio mass spectrometry; MS = mass spectrometry; OES = optical emission spectrometry; WS-CRDS = wavelength scanned cavity ring-down spectroscopy.

5.2.3 Injection Zone Monitoring

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

5.2.3.1 Objectives

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

- Calibrate the numerical models that will be used to help track CO_2 and pressure in the injection zone.
- Guard against over-pressuring, which could induce unwanted fracturing of the injection zone or the overlying confining zone(s).
- Determine the need for well rehabilitation.
- Assess injection zone properties (e.g., permeability, porosity, reservoir size) within progressively larger areas of the reservoir as the pressure front advances.

Data collection will be accomplished by monitoring pressure in wells completed in the injection zone, including injection wells, single-level (i.e., single discrete depth interval) monitoring wells, and possibly a multi-level monitoring well. Temperature and electrical conductivity will also be monitored at all well locations with a downhole combined pressure/temperature/electrical conductivity sensor. Temperature monitoring provides an additional benefit when the temperature of the injected CO_2 is sufficiently different from ambient reservoir temperatures, providing another indication of CO_2 plume arrival at monitoring well locations.

Specific objectives for aqueous monitoring of mixed hypersaline/CO_2 fluids in injection zone wells include the following:

- Aid in assessing the lateral and vertical extent of injected CO_2 over time within the injection zone.
- Characterize geochemical changes caused by interaction between the injected CO_2 and the host formation/fluids within the injection zone (i.e., pH, Eh, metal mobility, precipitation/dissolution).
- Characterize the fraction of aqueous solution and $scCO_2$ at selected locations in the injection zone within/near the CO_2 plume (as identified by cross-borehole geophysical surveys).

Fluid samples will be collected from monitoring wells completed in the injection zone before, during, and after CO_2 injection. The samples will be analyzed for chemical parameter changes that are indicators of the presence of CO_2 and/or reactions caused by the presence of CO_2.

5.2.3.2 Monitoring Approach

The post-injection monitoring period will nominally extend over at least a 50-year period, or as required to demonstrate that the injected CO_2 does not pose a threat to USDW aquifers (see Section 7.2).

Baseline pressure monitoring will involve the installation and testing of pressure sensors in the injection well and monitoring wells and collection of pressure data for approximately 1 year prior to the start of injection. Thus, baseline injection zone pressure monitoring cannot be initiated until the wells have been installed. Baseline aqueous monitoring is required to characterize the background injection zone fluid chemistry and provide a measure for comparison during and after injection operations. Baseline monitoring will involve collection and analysis of a minimum of three rounds of aqueous samples from each well completed in the target injection zone prior to initiation of CO_2 injection. If time allows, additional samples may be collected to aid in assessing the variability in the analytical parameters.

During the 20-year active injection phase, continuous (i.e., uninterrupted) monitoring of pressure will be conducted in injection zone monitoring wells and the CO_2 injection wells. The pressure gauges will be removed from the monitoring wells only when they require maintenance or when necessitated by other activities (e.g., well maintenance). In addition, all injection zone monitoring wells will be sampled on a regular basis to quantify CO_2 arrival times and transport processes. Injection wells will not be sampled during the operational phase because this would interfere with injection operations. However, the CO_2 injection stream will be monitored/sampled during this phase and the injection wells will be sampled after the conclusion of the injection period. Aqueous samples will be analyzed for the same parameters (see Section 5.2.2.3) that are measured during the baseline monitoring period. Monitoring data will be continuously evaluated throughout the active injection phase and if specific analytes are found to be of little benefit, they will be removed from the analyte list.

Post-injection monitoring data will be evaluated to determine when the injected CO_2 can no longer affect the USDW aquifers. This demonstration requires knowledge of pressure data for the injection reservoir; therefore, pressure monitoring in wells in the injection reservoir will continue throughout the post-injection monitoring period. At least two wells in the injection zone will be retained for this purpose. Monitoring of the injection zone fluids is not required during this phase of the project, but periodic samples may be collected to characterize longer-term geochemical changes occurring within the injection zone. Aqueous monitoring of injection zone fluids during this phase, if performed, will be performed at a reduced frequency (i.e., every 5 years).

5.2.3.3 Pressure Monitoring

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

Pressure in the injection zone will be monitored at several well locations (see the conceptual monitoring network design shown in Figure 5.1), including the injection wells, one single- or multi-level injection zone monitoring well located inside the projected 5-year plume extent, and two single-level Mount Simon monitoring wells located within the projected 5- to 22-year CO_2 plume extent.

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

Continuous monitoring of injection zone pressure and temperature will be performed with sensors installed in wells that are completed in the injection zone. Pressure and temperature monitoring in the injection well and all monitoring wells will be performed using a real-time monitoring system with surface readout capabilities so that pressure gauges do not have to be removed from the well to retrieve data. The injection zone multi-level monitoring well is designed to monitor multiple discrete depth intervals within the Mount Simon and Elmhurst sandstones. Similar to the injection wells, this well will be instrumented to provide real-time pressure data with surface readout capabilities. Power for the injection well will be provided by a dedicated line power supply. Power for all monitoring wells will be provided by a stand-alone solar array with battery backup so that a dedicated power supply to these more distal locations is not required.

The following measures will be taken to ensure that the pressure gauges are providing accurate information on an ongoing basis:

- High-quality (high-accuracy, high-resolution) gauges with low drift characteristics will be used.
- Gauge components (gauge, cable head, cable) will be manufactured of materials designed to provide a long life expectancy for the anticipated downhole conditions.
- Upon acquisition, a calibration certificate will be obtained for every pressure gauge. The calibration certificate will provide the manufacturer's specifications for range, accuracy (% full scale), resolution (% full scale), and drift (< psi per year) and calibration results for each parameter. The calibration certificate will also provide the date that the gauge was calibrated and the methods and standards used.
- Gauges will be installed above any packers so they can be removed if necessary for recalibration by removing the tubing string. Redundant gauges may be run on the same cable to provide confirmation of downhole pressure and temperature.
- Upon installation, all gauges will be tested to verify they are functioning (reading/transmitting) correctly.
- Gauges will be pulled and recalibrated whenever a workover occurs that involves removal of tubing. A new calibration certificate will be obtained whenever a gauge is recalibrated.

5.2.3.4 Aqueous Monitoring

Periodically, fluid samples will be collected from the monitoring wells completed in the injection zone (see sampling and analysis requirements in Section 5.2.2.3). Because of their proximity to the injection wells, a higher sampling frequency is warranted for the near-field single- or multi-level monitoring well, which will be located within the predicted 2- to 5-year plume, than for the single-level monitoring wells, which will be located within the 5- to 22-year plume. The sampling frequency for all wells may need to be adjusted as the CO_2 plume approaches the outer wells. Fluid samples will be collected using an appropriate method to preserve the fluid sample at injection zone temperature and pressure conditions. Examples of appropriate methods include using a bomb-type sampler (e.g., Kuster sampler) after pumped or swabbed purging of the sampling interval, using a Westbay sampler, or using a pressurized U-tube sampler (Freifeld et al. 2005). These types of pressurized sampling methods are needed to collect the two-phase fluids (i.e., aqueous and scCO_2 solutions) for measurement of the percent water and CO_2 present at the monitoring location.

Fluid samples will be analyzed for parameters that are indicators of CO_2 dissolution (Table 5.4), including major cations and anions, selected metals, general water-quality parameters (pH, alkalinity, TDS, specific gravity), and any tracers added to the CO_2 stream. Changes in major ion and trace element geochemistry are expected in the injection zone, but the arrival of proposed fluorocarbon or sulfonate tracers (co-injected with the CO_2) should provide an improved early-detection capability, because these compounds can be detected at 3 to 5 orders of magnitude lower relative concentration. Analysis of carbon and oxygen isotopes in injection zone fluids and the injection stream ($^{13/12}C$, $^{18/16}O$) provides another potential supplemental measure of CO_2 migration. Where stable isotopes are included as an analyte, data quality and detectability will be reviewed throughout the active injection phase and discontinued if these analyses provide limited benefit.

5.2.3.5 Geophysical Monitoring

A suite of indirect geophysical monitoring methods will be evaluated and tested to assess their efficacy and cost effectiveness for monitoring the spatial extent, evolution, and fate and transport of the injected CO_2 plume. Indirect monitoring methodologies under consideration are listed in Table 5.2 and measurement frequencies (if selected for deployment) are provided in Table 5.3. All methods will be evaluated during the design, construction, and initial operational phase (Phase IV) of the project and the most promising and cost-effective method(s) will be selected to carry forward through the operational phases.

5.2.4 CO_2 Injection Process Monitoring

This section describes the measurements and sampling methodologies that will be used to monitor the chemical and physical characteristics of the CO_2 injection stream.

5.2.4.1 Continuous Monitoring of the CO_2 Injection Process

Continuous Recording of Injection Mass Flow Rate

The mass flow rate of CO_2 injected into the well field will be measured by a flow meter skid with a Coriolis mass flow transmitter for each well. Each meter will have analog output (Micro Motion Coriolis Flow and Density Meter Elite Series or similar). A total of six flow meters will be supplied, providing for two spare flow meters to allow for flow meter servicing and calibration. Valving will be installed to select flow meters for measurement and for calibration. A single flow prover will be installed to calibrate the flow meters, and piping and valving will be configured to permit the calibration of each flow meter. The flow transmitters will each be connected to a remote terminal unit (RTU) on the flow meter skid. The RTU will communicate with the Control Center through the well annular pressure maintenance and monitoring system (WAPMMS) programmable logic controller (PLC) located at the injection well site. The flow rate into each well will be controlled using a flow-control valve located in the CO_2 pipeline associated with each well. The control system will be programmed to provide the desired flow rate into three of the four injection wells, with the one remaining well receiving the balance of the total flow rate.

Continuous Recording of Injection Pressure

The pressure of the injected CO_2 will be continuously measured for each well at a regular frequency by an electronic pressure transmitter with analog output mounted on the CO_2 line associated with each injection well at a location near the wellhead. The transmitter will be connected to the WAPMMS PLC at the injection well site.

Continuous Recording of Injection Temperature

The temperature of the injected CO_2 will be continuously measured for each well at a regular frequency by an electronic temperature transmitter. The temperature transmitter will be mounted in a temperature well in the CO_2 line at a location close to the pressure transmitter near the wellhead. The transmitter will be connected to the WAPMMS PLC located at the injection well site.

5.2.4.2 Injection Stream Analysis Parameters

According to the requirements of 40 CFR 146.90 (Testing and Monitoring Requirements) of the Class VI UIC Regulation, analysis of the CO_2 stream is required with sufficient frequency to provide data representative of its chemical and physical characteristics. Based on the anticipated composition of the CO_2 stream, a list of parameters was identified for analysis (Chapter 4.0, Table 4.1). Samples of the CO_2 stream will be collected regularly (e.g., quarterly) for chemical analysis.

5.2.4.3 Sampling Method

Grab samples of the CO_2 stream will be obtained for analysis of gases, including CO_2, O_2, H_2S, Ar, and water moisture. Samples of the CO_2 stream will be collected from the CO_2 pipeline at a location where the material is representative of injection conditions. A sampling station will be installed in the ground or on a structure close to the pipeline and connected to the pipeline via small-diameter stainless steel tubing to accommodate sampling cylinders that will be used to collect the samples. A pressure regulator will be used to reduce the pressure of the CO_2 to approximately 250 psi so that the CO_2 is in the gas state when collected rather than a supercritical liquid. Cylinders will be purged with sample gas (i.e., CO_2) prior to sample collection to remove laboratory-added helium gas and ensure a representative sample.

5.3 Injection Well Testing and Monitoring

This section describes the testing and monitoring activities that will be performed during the service life of the injection wells to routinely assess their mechanical integrity. Initial (i.e., baseline) mechanical integrity testing that will be performed on the injection wells prior to the start of CO_2 injection is discussed in the Construction and Operations Plan (Chapter 4.0).

5.3.1 Pressure Fall-Off Testing

Pressure fall-off testing is required upon completion of the injection wells prior to their operation (i.e., injection) to characterize reservoir hydrogeologic properties (40 CFR 146.87(e)(1)) and at least once every 5 years once injection operations begin (40 CFR 146.90(f)) to confirm site-characterization information, assess reservoir and well conditions, and inform AoR reevaluations. Pressure fall-off tests conducted after the start of CO_2 injection operations will provide the following information:

- confirmation of hydrogeologic reservoir properties
- long-term pressure buildup in the injection reservoir(s) due to CO_2 injection over time
- average reservoir pressure, which can be compared to modeled predictions of reservoir pressure to verify that the operation is responding as modeled/predicted and identify the need for recalibration of the AoR model in the event that the monitoring results do not match expectations
- formation damage (skin) near the well bore, which can be used to diagnose the need for well remediation/rehabilitation.

The EPA has not issued guidance for conducting pressure fall-off testing at GS sites; however, guidance is available for conducting these tests for Class I UIC wells (see for example EPA 2002, 1998). These guidelines will be followed when conducting pressure fall-off tests for the FutureGen 2.0 Project.

In the pressure fall-off test, flow is maintained at a steady rate for a period of time, then injection is stopped, the well is shut-in, and bottom-hole pressure is monitored and recorded for a period of time sufficient to make a valid observation of the pressure fall-off curve. Downhole or surface pressure gauges will be used to record bottom-hole pressures during the injection period and the fall-off period. Pressures will be measured at a frequency that is sufficient to measure the changes in bottom-hole pressure throughout the test period, including rapidly changing pressures immediately following cessation of injection. The fall-off period will continue until radial flow conditions are observed, as indicated by stabilization of pressure and leveling off of the pressure derivative curve. The fall-off test may also be truncated if boundary effects are encountered, which would be indicated as a change in the slope of the derivative curve, or if radial flow conditions are not observed. In addition to the radial flow regime, other flow regimes may be observed from the fall-off test, including spherical flow, linear flow, and fracture flow. Analysis of pressure fall-off test data will be done using transient-pressure analysis techniques that are consistent with EPA guidance for conducting pressure fall-off tests (EPA 1998, 2002).

5.3.2 Mechanical Integrity Testing During Service Life of Well

This section describes the mechanical integrity tests that will be conducted during the period of active CO_2 injection. Initial (i.e., baseline) mechanical integrity testing (MIT) that will be performed on the injection wells prior to the start of CO_2 injection as discussed in the Construction and Operations Plan (Chapter 4.0, Section 4.3). Regular MIT will be conducted after CO_2 injection commences to ensure that the well has adequate internal and external mechanical integrity as injection continues.

Internal Mechanical Integrity Testing

Internal mechanical integrity will be continuously monitored by monitoring the annular pressure in the well. This will be accomplished automatically by the WAPMMS, as described in the Construction and Operations Plan (Section 4.3). In addition to continuous monitoring of the annular pressure, an APT (annular pressure test) will be performed whenever the tubing or packer is removed from the well (e.g., during well workovers) and prior to resuming injection operations.

External Mechanical Integrity Testing

As discussed in the Construction and Operations Plan (Section 4.3, an initial (baseline) temperature log and/or oxygen-activation log will be run on the well after well construction but prior to commencing CO_2 injection. These baseline log(s) will serve as a reference for comparing future temperature and/or oxygen-activation logs for evaluating external mechanical integrity. The following sections describe temperature logging and oxygen-activation logging during the service life of the well. A third type of mechanical integrity test—a RTS—is also described. This method may be used instead of or in addition to temperature logging or oxygen-activation logging, if needed, to help explain results.

Temperature Logging

Temperature logs can be used to identify fluid movement along channels adjacent to the well bore. In addition to identifying injection-related flows behind casing, temperature logs can often locate small casing leaks.

Injection of CO_2 will have a cooling or heating effect on the natural temperature in the storage reservoirs, depending on the temperature of the injected CO_2 and other factors. Once injection starts, the flowing temperature will stabilize quickly (assuming conditions remain steady). When an injection well is shut-in for temperature logging, the well bore fluid begins to revert toward ambient conditions. Zones that have taken injectate, either by design or not, will exhibit a "storage" signature on shut-in temperature surveys (storage signatures are normally cold anomalies in deeper wells, but may be cool or hot depending on the temperature contrast between the injectate and the reservoir). Losses behind pipe from the injection zone can be detected on both flowing and shut-in temperature surveys and exhibit a "loss" signature.

For temperature logging to be effective for detecting fluid leaks, there should be a contrast in the temperature of the injected CO_2 and the reservoir temperature. The greater the contrast in the CO_2 when it reaches the injection zone and the ambient reservoir temperature, the easier it will be to detect temperature anomalies due to leakage behind casing. Based on data from the stratigraphic well, ambient bottom-hole temperatures in the Mount Simon Sandstone are expected to be approximately 100°F; the temperature of the injected CO_2 is anticipated to be on the order of 72°F to 90°at the surface (depending on time of year) but will undergo some additional heating as it travels down the well. After the baseline (i.e., prior to injection) temperature log has been run to determine ambient reservoir temperature in each well, it will be possible to determine whether there will be sufficient temperature contrast to make the temperature log an effective method for evaluating external mechanical integrity. Temperature logging would be conducted through the tubing and therefore would not require removal of the tubing and packer from the well.

The Alliance will consult the EPA Region 5 guidance for conducting temperature logging (EPA 2008) when performing this test.

Oxygen-Activation Logging

Oxygen activation is a geophysical logging technique that uses a pulsed-neutron capture tool to quantify the flow of water in or around a borehole. For purposes of demonstrating external mechanical integrity, a baseline oxygen activation will be run prior to the start of CO_2 injection and compared to later runs to determine changing fluid flow conditions adjacent to the well bore (i.e., formation of channels or other fluid isolation concerns related to the well).

The pulsed-neutron tool emits high-energy neutrons that interact with water molecules present in the casing-formation annular space, among others. This temporarily activates oxygen (^{16}O) to produce an isotope of nitrogen (^{16}N) that decays back to oxygen with a half-life of 7.1 seconds and emits an easily detected gamma ray. Typical pulsed-neutron capture tools have two or three gamma-ray detectors (above and below the neutron source) to detect the movement of the activated molecules, from which water velocity can then be calculated. The depth of investigation for oxygen-activation logging is typically less than 1 ft; therefore, this log type provides information immediately adjacent to the well bore.

Repeat runs will be made under conditions that mimic baseline conditions (e.g., similar logging speeds and tool coefficients) as closely as possible to ensure comparability between baseline and repeat data.

The Alliance will consult the EPA Region 5 guidance for conducting the oxygen-activation logging (EPA 2008) when performing this test.

5.3.2.2 Corrosion Monitoring

This section discusses the measures that will be taken to monitor corrosion of well materials, including tubulars (i.e., casing, tubing) and cement; planned monitoring frequencies are provided in Table 5.3. Note that cement evaluation beyond the preliminary cement-bond log is not required for Class VI wells under MIT or corrosion monitoring (40 CFR 146.89 and 146.90). However, it is recognized that cement integrity over time can influence the mechanical integrity of an injection well. Therefore, cement-evaluation logs will be run when tubing is removed from the well (i.e., during well workovers). In addition, while they are not required for corrosion monitoring, casing inspection logs will also be run when tubing is removed from the well (i.e., during well workovers).

Casing and Tubing

Corrosion of well materials will be monitored using the corrosion coupon method. Corrosion monitoring of well casing and tubing materials will be conducted using coupons placed in the CO_2 pipeline. The coupons will be made of the same material as the long string of casing and the injection tubing. The coupons will be removed quarterly and assessed for corrosion using the American Society for Testing and Materials (ASTM) G1-03, Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens (ASTM 2011). Upon removal, coupons will be inspected visually for evidence of corrosion (e.g., pitting). The weight and size (thickness, width, length) of the coupons will also be measured and recorded each time they are removed. Corrosion rate will be calculated as the weight loss during the exposure period divided by the duration (i.e., weight loss method).

Casing and tubing will also be evaluated periodically for corrosion throughout the life of the injection well by running casing inspection (wireline) logs. The frequency of running these tubing and casing inspection logs will be determined based on site-specific parameters and well performance. Wireline tools are lowered into the well to directly measure properties of the well tubulars that indicate corrosion. Four types of wireline tools are available for assessing corrosion of well materials—mechanical, electromagnetic, ultrasonic, and videographic. Mechanical, electromagnetic, and/or ultrasonic tools will be used primarily to monitor well corrosion (Table 5.6). These tools, or comparable tools from alternate vendors, will be used to monitor the condition of well tubing and casing.

Table 5.6. Examples of Wireline Tools for Monitoring Corrosion of Casing and Tubing

	Mechanical	Ultrasonic	Electromagnetic
Tool Name	Multifinger Imaging Tool[(a)]	Ultrasonic Imager Tool[(a)]	High-Resolution Vertilog[(b)]
Type	Mechanical	Ultrasonic	Electromagnetic
Parameter(s) Measured	Internal radius; does not measure wall thickness	Inner diameter, wall thickness, acoustic impedance, cement bonding to casing Up to 180 measurements per revolution	Magnetic flux leakage (internal and external) Full 360 degree borehole coverage
Tool O.D. (in.)	1.6875, 2.75, 4 (multiple versions of available)	3.41 to 8.625	2.2 to 8.25
Tubular Size That Can Be Measured Min/Max (in.)	2/4.5, 3/7, 5/10 (multiple versions of available	4.5/13.375	4.5/9.625
Comments, limitations, special requirements, etc.	Typically run on memory using slickline. Can also be run in surface real-time mode.	Can detect evidence of defects/corrosion on casing walls (internal/external), quality of cement bond to pipe, and channels in cement. Moderate logging speed (30 ft/min) is possible.	Can distinguish between general corrosion, pitting, and perforations. Can measure pipe thickness. High logging speed (200 ft/min) is possible. Cannot evaluate multiple strings of tubular simultaneously.

(a) Schlumberger Limited
(b) Baker Hughes, Inc.

Mechanical casing evaluation tools, referred to as calipers, have multiple "fingers" that measure the inner diameter of the tubular as the tool is raised or lowered through the well. Modern-day calipers have several fingers and are capable of recording information measured by each finger so that the data can be used to produce highly detailed 3D images of the well. An example caliper tools is Schlumberger's Multifinger Imaging Tool (Table 5.6). This tool is available in multiple sizes to accommodate various sizes of well tubing and casing.

Ultrasonic tools are capable of measuring wall thickness in addition to the inner diameter (radius) of the well tubular. Consequently, these tools can also provide information about the outer surface of the casing or tubing. Examples of ultrasonic tools include Schlumberger's Ultrasonic Casing Imager (UCI) and Ultrasonic Imager (USI). The USI can also be used for cement evaluation, as discussed below. Specifications for the USI tool are listed in Table 5.6.

Electromagnetic tools are able to distinguish between internal and external corrosion effects using variances in the magnetic flux of the tubular being investigated. These tools are able to provide mapped (circumferential) images with high resolution such that pitting depths, due to corrosion, can often be accurately measured. An example electromagnetic tool is Baker Hughes' High-Resolution Vertilog (Table 5.6).

Mechanical caliper tools are excellent casing/tubing evaluation tools for internal macro-scale features of the casing/tubing string. Ultrasonic tools, such as the USI, are able to further refine the scale of feature detection and can evaluate cement condition. However, electromagnetic tools offer the most sensitive means for casing/tubing corrosion detection. When conducting casing inspection logging, both an ultrasonic and an electromagnetic tool will be run to assess casing corrosion conditions (the ultrasonic tool will also be run to provide information on cement corrosion).

Well Cement

The cement associated with the long-string casing may be susceptible to corrosion where it is exposed to injected CO_2. Several measures will be taken during the construction and operation of the injection well to monitor the condition of the cement. As described in the Construction and Operations Plan (Chapter 4.0, Section 4.2.3), a corrosion-resistant cement will be used in this casing section to mitigate corrosion that could lead to the formation of channels that could transmit fluid. Furthermore, the condition of the cement will be determined initially when the casing string is cemented using cement-bond logging, and external mechanical integrity tests will be conducted periodically using temperature surveys or other means to look for evidence of fluid movement behind casing that could be caused by cement corrosion. In addition to these measures, cement-evaluation logging will be conducted whenever the tubing is removed from the injection well (i.e., during well workovers).

Types of cement-bond logging tools include conventional CBL (e.g., Baker Hughes' acoustic cement-bond log, CBL), acoustic pad-based (e.g., Baker Hughes' segmented bond tool [SBT]), and ultrasonic (e.g., Schlumberger's USI). Table 5.7 summarizes information for example acoustic and ultrasonic casing evaluation tools. These tools, or similar tools, from alternate vendors may be used to monitor the condition of well tubing and casing.

Table 5.7. Examples of Wireline Tools for Evaluating Cement Behind Casing

	Acoustic Tool	Acoustic Pad Tool	Ultrasonic Tool
Tool Name	Slim Cement Mapping Tool[(a)]	Segmented Bond Tool [(b)]	Ultrasonic Imager Tool[(a)]
Type	Acoustic	Acoustic	Ultrasonic
Parameter(s) measured	Acoustic signal attenuation VDL	Acoustic signal attenuation 360 degree borehole coverage VDL	Inner diameter, wall thickness, acoustic impedance, cement bonding to casing Up to 180 measurements per revolution
Tool O.D. (in.)	11.0625 and 2.0625	3.625	3.41 to 8.625
Tubular Size That Can Be Measured Minimum/ Maximum (in.)	2.375/8.875	4.5/13.375	4.5/13.375
Comments, limitations, special requirements, etc.	Can be run through tubing. Gives a radial map image of cement sheath	Not affected by borehole fluid type presence of gas. Can detect channeling and gives VDL output.	Can detect evidence of defects/corrosion on casing walls (internal/external), quality of cement bond to pipe, and channels in cement. Moderate logging speed (30 ft/min) is possible.

(a) Schlumberger Limited
(b) Baker Hughes, Inc.
NA = not available.

A traditional, acoustic bond logging tool is a simple arrangement that requires an acoustic signal transmitter and one or more receivers. The transmitted signal strength is compared to the strength of the received signal to qualitatively infer the quality/amount of cement present behind the casing string (where a more attenuated return signal indicates a better cement bond). The received signal's wave train is often represented in a variable-density log (VDL) display where various signal arrivals can be inferred (e.g., mud, casing, cement, formation). However, these traditional acoustic tools often require an omni-directional averaging method, which results in a limited ability to detect channeling in the cement sheath. Therefore, some tools offer multiple receivers, which reduces the radial averaging requirement and allows for a presentation of a radial image (e.g., Schlumberger's slim cement mapping tool).

Baker Hughes' pad-based SBT uses an acoustic transmitter/receiver setup similar to a traditional acoustic logging tool but instead uses six pads that make contact with the inner casing walls. This technology boosts the signal-to-noise ratio resulting in higher data quality and interpretability. In addition, each pad is able to measure a 60-degree swath of the cross-sectional well-bore area, which allows for enhanced channel detection in the cemented annular space. Data collected using the SBT can also be presented as a VDL.

An ultrasonic casing evaluation tool, specifically Schlumberger's USI, is an example of a wireline logging tool that is capable of assessing the condition of the cement behind casing at the same time that the casing integrity is being evaluated. One limitation of the USI, specifically, is that only the casing-to-cement bond is evaluated. That is, no direct information is collected on the cement-to-formation contact. In addition, a VDL presentation with any ultrasonic tool is not possible. For this reason, two bond logs are often collected, one ultrasonic and one acoustic, where the interpretation from each can be verified using the other.

For cement evaluation, both an ultrasonic and an acoustic logging tool will be run when conducting casing inspection logging because information provided by ultrasonic tools is limited to the cement-to-casing bond; whereas, the condition of the cement beyond the casing-cement contact will be provided by the acoustic logging tool. The cement associated with the section of long-string casing that spans the confining layers will be the primary focus of the cement-evaluation logging.

5.3.3 Well Annulus Pressure Maintenance and Monitoring System

The injection wells will be constructed with an annulus pressure control system to maintain annular fluid in each well at a prescribed pressure. A comprehensive automated WAPMMS will be designed and implemented. The preliminary WAPMMS design specifications presented in this section may be revised before the system is constructed.

The WAPMMS includes piping, instrumentation valves, controls, and other equipment to accomplish several functions, including the following:

- Maintain a prescribed pressure on the annular fluid in the well and a downward pressure differential across the packer. If annular (surface) pressure must be maintained at a value greater than the injection pressure, the maximum annulus pressure will not exceed a value that is more than ~200 psi greater than injection pressure at the surface. Otherwise, the maximum annulus (surface) pressure will not exceed a value that would result in a pressure at the top of the packer that is greater than the pressure inside the tubing when the bottom-hole injection pressure is at the maximum allowable pressure

- Automatically deliver annular fluid to the well when the fluid volume in the well decreases because of temperature and/or pressure changes or leaks in the well.
- Automatically remove annular fluid from the wells when the fluid volume in the well increases because of temperature and/or pressure changes.
- Continuously monitor injection well parameters including annular pressure, wellhead pressure and temperature, and bottom-hole pressure and temperature.
- Monitor parameters (e.g., pressure, temperature, fluid levels, air pressure) associated with the pressure-maintenance system.
- Automatically cease CO_2 injection to the wells when injection pressure or annulus pressure fall outside of prescribed limits.

During operation, the annular fluid pressurization system will be monitored and important parameters will be electronically recorded for documentation and review. The system will be equipped with alarms to warn of impending noncompliance or out-of-operating-parameter excursions.

5.3.4 Injection Well Control and Alarm System

The injection process will be monitored by the WAPMMS, an integrated system of equipment (tanks, lines, pumps, valves) and instrumentation (pressure and temperature transmitters) that will be capable of detecting when injection conditions are out of acceptable limits and responding by either adjusting conditions or halting injection. The system is designed to operate automatically with minimal operator intervention. The proposed control system for the WAPMMS consists of a local PLC interfaced with the control room (located at the power plant) distributed control system via a communications network. The WAPMMS PLC will provide control and monitoring of the injection pressure, annular pressure, and related parameters associated with the WAPMMS.

5.4 Monitoring, Verification, and Accounting

The testing and monitoring activities described in Section 5.2 are designed to collect the data necessary to verify that CO_2 is effectively sequestered within the targeted deep geologic formation and track the total mass of CO_2, including any potential injection zone containment loss and migration into overlying formations. The monitoring network design includes one ACZ monitoring well installed to just above the primary confining zone for enhanced early-detection capability. Such monitoring, along with direct and indirect (i.e., geophysical) measurements made within the injection zone, will facilitate timely and effective indications of CO_2 migration beyond the injection zone. The monitoring design will also consider inclusion of other surface or near-surface-monitoring approaches that provide for supplemental, broad-area indicators of CO_2 leakage along unidentified preferential transport pathways. As discussed in Section 3.2, no preferential pathways are known to exist within the defined AoR for the Morgan County storage site. These proposed secondary near-surface-monitoring systems will ensure that any potential impacts on near-surface environments, including impacts on shallow USDW aquifers, are quantitatively assessed relative to baseline conditions. This multi-component “lines of evidence” approach to monitoring and detection will increase the likelihood that any significant release of CO_2 from the injection zone is identified and mitigated in a timely manner.

Throughout the operational and post-operational phases of the project, collected monitoring data and numerical simulation will be used to evaluate the CO_2 mass balance for the injection zone. The mass balance will be based on the mass of CO_2 injected, the estimated mass present within the injection zone (based on direct and indirect monitoring techniques), and any identified containment loss. The model will be used to evaluate observed tracer and/or CO_2 arrival responses and predict when arrival will occur at more distal locations and later times. If significant discrepancies exist between the mass injected and the predicted/observed spatial extent of the CO_2 plume, this will provide additional evidence that injection zone containment loss may be occurring. If a release is confirmed through mass balance analysis and/or direct measurement of impacts occurring above the primary confining zone, the environmental release model will be used to estimate the magnitude of the leak and assess potential migration rates and pathways for CO_2 transport to shallower depths. Numerical models will be routinely validated and recalibrated to observed responses and will be used to guide modification of the monitoring program if required.

5.5 Schedule

There will be three general phases of aqueous monitoring: baseline monitoring, active injection monitoring, and post-injection monitoring. The approximate duration of these defined phases is 3 years, 20 years, and 50 years, respectively.

5.6 Data Management

The Project Data Management Plan[1] identifies how the information and data collected or generated for the storage facility task will be stored and organized to support all phases of the project. It describes the institutional responsibilities and requirements for managing relevant data, including the types of data to be managed and how the data will be managed and made available to prospective users. There are various needs/uses for data and information throughout the life of the project. These needs include site selection and evaluation, characterization, regulatory permitting, storage facility design, operation and monitoring, and post-closure monitoring. Data and information management needs will also change over the life of the project, and, given the long-term nature of the project life cycle, there will be many organizational and personnel changes, as well as major changes in the technologies used to acquire, record, and manage data and information. As these changes take place the data management strategies and tools will be revised and updated, as needed.

The primary objectives of the monitoring program are to track the lateral extent of the CO_2 plume and the pressure front within the target reservoir, characterize any geochemical or geomechanical changes that occur within the reservoir and overlying caprock, determine whether the injected CO_2 is effectively contained within the injection zone, and, if any release is indicated, quantify the size of the leak and the potential impacts on USDW aquifer water quality. The monitoring program will also be designed to identify and assess any impacts on near-surface soil-gas composition, atmospheric CO_2 concentrations, or ecological receptors. The data management plan is designed to facilitate compliance with EPA-specified requirements in 40 CFR 146.91. Particular care will be taken to provide secure and easily retrievable

[1] Last GV, MA Chamness, MT Schmick, and DC Lanigan. June 2011. *FutureGen Support Project Data Management Plan*. (Accessed at FUTUREGEN 2.0 > Site Characterization > Storage Facility Task > 1.0 Task Management > Project Data Management > Data Management Plan)

storage of all forms of data throughout the life of the GS project and for 10 years after site closure consistent with 40 CFR 146.91 (f). All required reports, submittals, and notifications will be issued to the EPA in an electronic format approved by the EPA.

The monitoring program is broken down into several tasks: reservoir monitoring (including continuous, quarterly, and periodic measurements/sampling), deep-leak-detection monitoring, USDW aquifer monitoring, soil-gas monitoring, atmospheric monitoring, and ecological monitoring. Each of these monitoring tasks produces different types of data and has different data management needs (input, storage, manipulation, querying, access/output). Thus, the data management program will develop and maintain a number of "semi-autonomous" databases under individual tasks, subject to their compatibility with an overarching distributed data management system. These individual heterogeneous databases will eventually all be linked to a centralized database and file archival system, eventually housed at a local visitor/training center.

A wide variety of monitoring data will be collected specifically for this project, under appropriate quality assurance protocols (e.g., screening data might have less stringent requirements than compliance monitoring data). These data will come in many different forms including hard copy, electronic image files, digitally collected, telemetered and recorded data, acquired digital data (e.g., remote sensing), and even physical samples. Each data form will require different data management protocols and storage/management tools from simple file management to relational databases to geographic information systems

Subject matter experts will screen, validate, and/or pre-process raw data (e.g., average high-frequency continuous data over various time intervals, or deconvolve composite analyses) to produce "science-ready" and/or "interpreted" data sets. Data with different levels of quality assurance documentation (e.g., legacy data vs compliance-driven data) and at different levels of processing/verification should all be managed separately. To this end, the following data classifications/groupings are defined:

- Level 0 – Legacy data with little or no substantial documentation or quality.
- Level 1 – Raw data (resulting from some procedure or technology).
- Level 1.5 – Cleaned raw data (raw data that has been scrubbed for duplicates, gaps, corrupted data, qualification flags, etc.). Need to capture the verification/validation/scrubbing procedures.
- Level 2 – Processed data (the cleaned or raw data that has been processed, normalized, or otherwise transformed using some model, code, algorithms, etc.). Need to capture the pedigree of how the data was processed—what code or algorithms were used (input and output files).
- Level 3 – Interpreted/subjective data sets (e.g., geologists' visual descriptions of cuttings and core, stratigraphic contacts, assumed/estimated parameter values). Need to capture assumptions, criteria, data sets, etc. forming the basis for interpretation.
- Level 4 – Averaged, upscaled, or statistically summarized or otherwise reconfigured parameter data sets destined for use as model/simulation input parameters. Need to capture methods, data sets, etc. used to generate input data.

The data management approach will consist of a number of different database/file management systems, each with its own data management protocols/procedures, etc. A detailed description of this relational database structure will be documented in the Project Data Management Plan.

5.7 Testing and Monitoring Plan Maintenance

This Testing and Monitoring Plan will be reviewed, at a minimum, after each reevaluation of the AoR, and amended as necessary. This reevaluation process will occur at least every 5 years. Results from the AoR reevaluation, which will include a comprehensive interpretation of the monitoring data, operational data, and any newly collected site-characterization data, will be used to assess the need for a Testing and Monitoring Plan amendment. Other conditions that would trigger a review of the Testing and Monitoring Plan include, but are not limited to 1) changes to (or the addition of) a Class VI injection well and/or significant changes to the monitoring network design, 2) changes to the AoR determination, 3) evidence of CO_2 migration through the caprock or other release-related changes in water quality, 4) well construction or mechanical integrity concerns, and 5) adverse events that require implementation of the Emergency Response Plan (Chapter 8.0 of this supporting documentation). Prior to amending the Testing and Monitoring Plan, findings will be discussed with the UIC Program Director to determine whether it is required.

5.8 Quality Assurance and Surveillance Plan

Data quality assurance and surveillance protocols adopted by the project will be designed to facilitate compliance with the requirements specified in 40 CFR 146.90(k). Quality Assurance (QA) requirements for direct measurements within the injection zone, above the confining zone, and within the shallow USDW aquifer that are critical to the MVA program (e.g., pressure and aqueous concentration measurements) are covered in Sections 5.2.2 and 5.2.3 above. QA requirements for selected geophysical methods, which provide indirect measurements of CO_2 nature and extent and are being tested for their applicability under site conditions, are not addressed in this plan. These measurements will be performed based on best industry practices and the QA protocols recommended by the geophysical services contractors selected to perform the work.

5.9 References

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