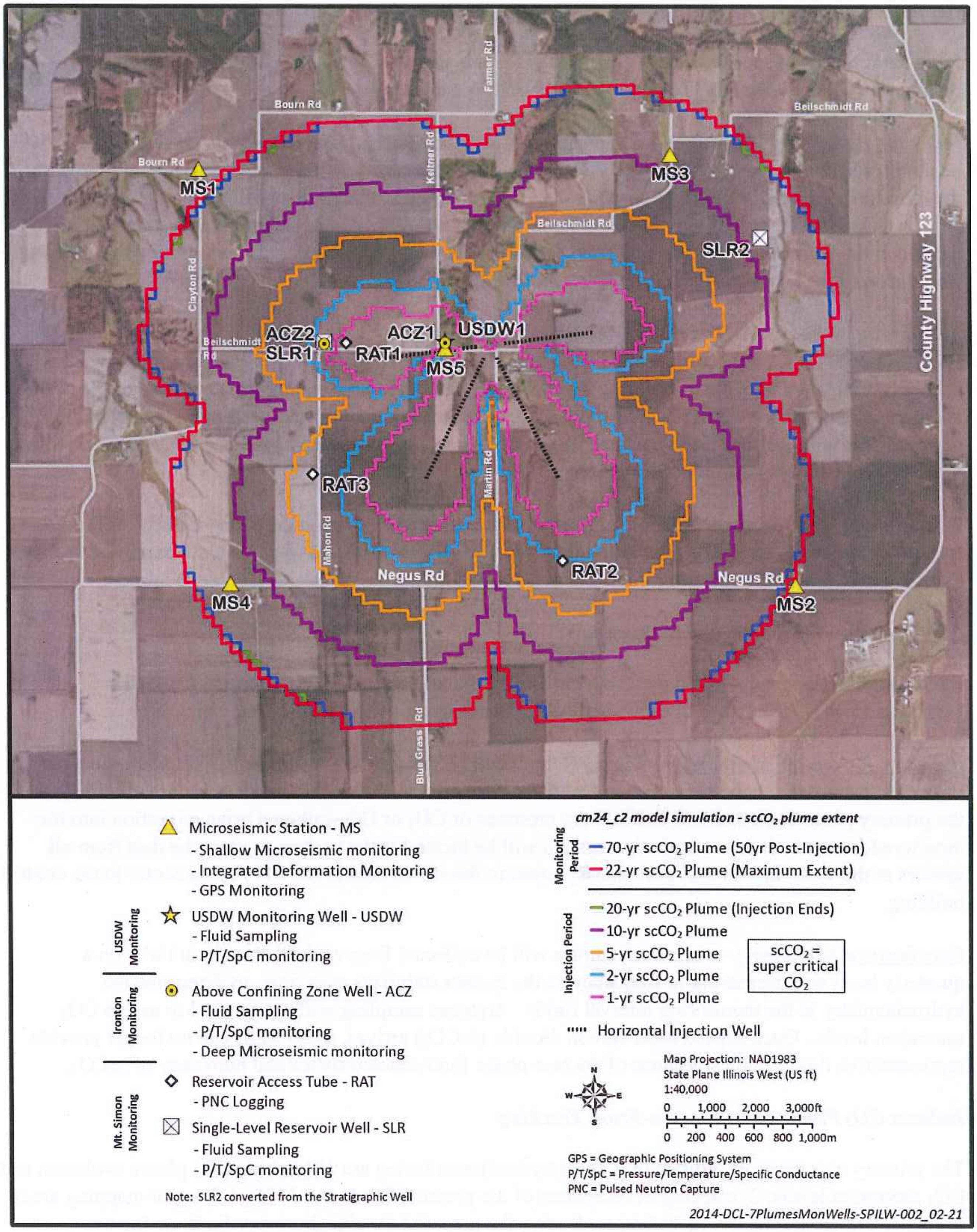

Figure A.3. Nominal Monitoring Well Layout and Modeled Supercritical CO_2 ($scCO_2$) Plume at different times. Note that the monitoring well locations are approximate and subject to landowner approval.

Groundwater Quality Monitoring

Fluid sampling (and subsequent geochemical analyses) and continuous monitoring of indicator parameters will be conducted at each ACZ and USDW monitoring well.

Indicator Parameter Monitoring – Fluid pressure, temperature, and specific conductance (P/T/SpC) will be monitored continuously. These are the most important parameters to be measured in real time within the monitoring interval of each well. These are the primary parameters that will indicate the presence of CO_2 or CO_2-induced brine migration into the monitored interval. A data-acquisition system will be located at the surface to store the data from all sensors at the well site and will periodically transmit the stored data to the MVA data center in the control building.

In addition, in the two ACZ wells, a fiber-optic cable with integral geophones (fiber Bragg grating optical accelerometer) will extend from ground surface to the monitoring interval (i.e., to the annulus casing packer [ACP] just above the monitoring interval); this cable will be strapped to the outside of the casing and permanently cemented in place to support the microseismic monitoring program. Data from the fiber-optic sensors will be transmitted back to the MVA data center via a local-area fiber-optic network where the data-acquisition system will be located.

Geochemical Monitoring – Aqueous samples will be collected from each ACZ and USDW well, initially on a quarterly basis and decreasing in frequency as the system stabilizes over time, to determine the hydrochemistry in the monitoring interval fluids.

CO_2 Plume and Pressure-Front Tracking

Fluid sampling (and subsequent geochemical analyses) and continuous monitoring of indicator parameters will be conducted at each single-level in-reservoir (SLR) monitoring well.

Indicator Parameter Monitoring – Fluid P/T/SpC will be monitored continuously. They are the most important parameters to be measured in real time within the monitoring interval of each well. They are the primary parameters that will indicate the presence of CO_2 or CO_2-induced brine migration into the monitored interval. A data-acquisition system will be located at the surface to store the data from all sensors at the well site and will periodically transmit the stored data to the MVA data center in the control building.

Geochemical Monitoring – Aqueous samples will be collected from each SLR well, initially on a quarterly basis and decreasing in frequency as the system stabilizes over time, to determine the hydrochemistry in the monitoring interval fluids. Aqueous sampling will not be used to assess CO_2 saturation levels. Once supercritical carbon dioxide ($scCO_2$) arrives, these wells can no longer provide representative fluid samples because of the two-phase fluid characteristics and buoyancy of $scCO_2$.

Indirect CO_2 Plume and Pressure-Front Tracking

The primary objectives of indirect (e.g., geophysical) monitoring are 1) tracking CO_2 plume evolution and CO_2 saturation levels; 2) tracking development of the pressure front; and 3) identifying or mapping areas of induced microseismicity, including evaluating the potential for slip along any faults or fractures identified by microseismic monitoring. Table A.4 summarizes potential geophysical monitoring technologies and identifies those included in the Testing and Monitoring Plan.

Pulsed-Neutron Capture Logging – The monitoring network will also include three reservoir access tube (RAT) installations designed for the collection of PNC logs to indirectly quantify CO_2 saturations within the Mount Simon injection zone or reservoir (Muller et al. 2007). PNC logging will serve as the primary measure for CO_2 saturation changes that occur within the injection zone. These monitoring points will be located within the predicted lateral extent of the 1- to 3-year CO_2 plume based on numerical simulations of injected CO_2 movement. The RAT locations were selected to provide information about CO_2 arrival at different distances from the injection wells and at multiple lobes of the CO_2 plume.

Geophysical Monitoring

Table A.4. Monitoring Technologies and Decision to Include in Monitoring Plans

Technology	Purpose	Analysis & Limitations
Pulsed-Neutron Capture Logging	Monitors CO_2 saturation changes along boreholes. Used for reservoir model calibration and leak detection.	Will provide quantitative CO_2 saturations. Sensitive only to region around the borehole.
Integrated Surface Deformation Monitoring	Monitors subtle changes in the Earth's surface due to geomechanical response to injection.	Will be able to measure expected deformation. Monitor for anomalies in pressure-front development. DInSAR can be difficult in vegetated areas.
Passive Microseismic	For locating fracture opening and slip along fractures or faults; may indicate location of the pressure front.	Can accurately detect seismic events. Not likely to detect limit of CO_2 plume.
Time-Lapse Gravity	Monitors changes in density distribution in the subsurface, caused by the migration of fluids. Relatively inexpensive.	Non-unique solution, must be used in conjunction with integrated surface deformation monitoring.

Passive Microseismic Monitoring – The objective of the microseismic monitoring network is to accurately determine the locations, magnitudes, and focal mechanisms of injection-induced seismic events with the primary goals of 1) addressing public and stakeholder concerns related to induced seismicity; 2) estimating the spatial extent of the pressure front from the distribution of seismic events; and 3) identifying features that may indicate areas of caprock failure and possible containment loss. The proposed seismic monitoring network consists of five shallow borehole stations, surface stations, and two deep borehole stations. The shallow borehole stations will be drilled to at least the uppermost competent bedrock (~100 m). Actual noise levels and sensor magnitude detection limits at the stations will not be determined until after the sensors have been emplaced and monitored for a period of time. The results of this preliminary evaluation will guide the location of a small number (fewer than five) of additional surface stations.

Deep borehole sensors will be clamped to the outside of the casing of the two ACZ monitoring wells and cemented in place. A 24-level three-component borehole array will be installed in each well. The use of 24-level arrays results in a slight improvement in event location, but more importantly offers redundant sensors in case of failure. Optical three-component accelerometers are technically optimal due to their designed long-term performance characteristics.

Time-Lapse Gravity – The objective of this technique is to estimate the areal extent of the CO_2 plume, based on observed changes in density distribution in the subsurface, caused by the migration of fluids. Gravity changes at the surface are expected to be small but averaging many measurements and/or analysis of long-term trends may allow for tracking of the CO_2 plume. The solution is non-unique and is most useful when combined with Differential Global Positioning System (DGPS) surveys and other integrated surface deformation methods and/or seismic surveys. The locations of permanent and proposed permanent station monuments are shown in Figure A.4.

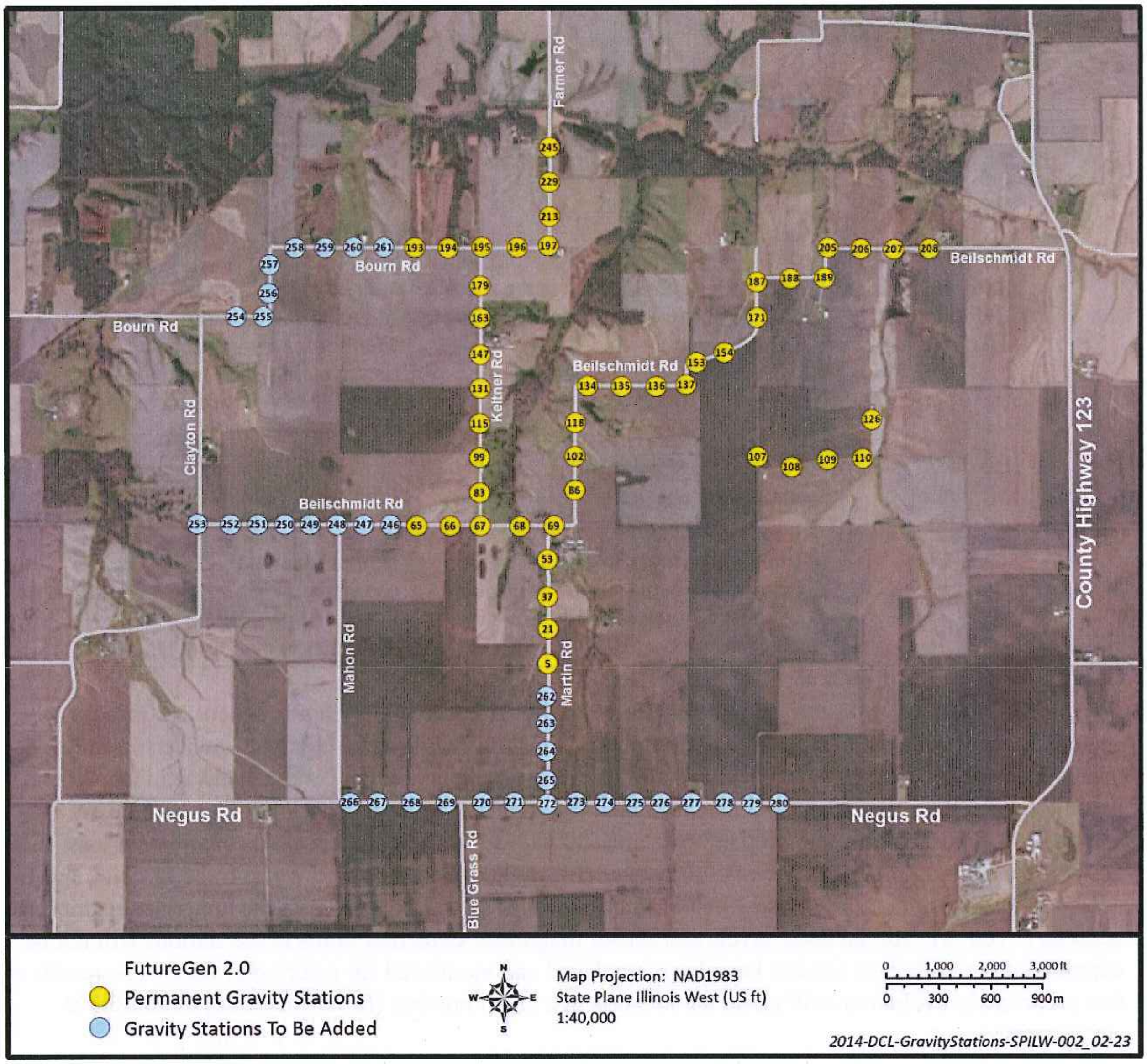

Figure A.4. Locations of Permanent and Proposed Permanent Gravity and Supplemental DGPS Stations

Integrated Deformation Monitoring – Integrated deformation monitoring integrates ground-surface data from permanent Global Positioning System (GPS) stations and tiltmeters, supplemented with annual DGPS surveys and larger-scale Differential Interferometric Synthetic Aperture Radar (DInSAR) surveys to detect and map temporal ground-surface deformation. The DInSAR and proposed GPS network are expected to resolve sub-centimeter surface changes and accurately measure the anticipated injection-induced surface deformation. Permanent GPS and tiltmeter stations will be co-located with the shallow microseismic locations and are expected to have the spatial coverage needed to characterize the overall shape and evolution of the geomechanical changes that occur as a result of CO_2 injection.

A.7 Quality Objectives and Criteria for Measurement Data

The primary goal of testing and monitoring activities is to verify that the Morgan County CO_2 storage site is operating as permitted and is not endangering any USDWs. The Class VI Rule requires that the owner or operator submit the results of testing and monitoring as part of the required semi-annual reports (40 CFR 146.91(a)(7)).

A.7.1 Quality Objectives

The overall Quality Assurance (QA) objective for testing and monitoring is to provide results, interpretation, and reporting that provide reasonable assurance that decision errors regarding compliance with permitting and protection of USDWs are unlikely. The EPA (2013 EPA 816-R-13-001 – Testing and Monitoring Guidance) provides a number of recommendations that can be used as qualitative measures/criteria against which the testing and monitoring results can be compared to evaluate compliance.

Mechanical Integrity Testing

Demonstrating and maintaining the mechanical integrity of a well is a key aspect of protecting USDWs from possible endangerment and a specific requirement for Class VI wells in the UIC Program. The Class VI Rule requires mechanical integrity testing (MIT) to be conducted prior to injection (40 CFR 146.87(a)(4)), during the injection phase (40 CFR 146.89), and prior to well plugging after injection has ceased (40 CFR 146.92(a)). The EPA further identified a number of acceptable MIT methods.

A Class VI well can be demonstrated to have mechanical integrity if there is no significant leak (i.e., fluid movement) in the injection tubing, packer, or casing (40 CFR 146.89(a)(1)), and if there is no significant fluid movement through channels adjacent to the injection well bore (40 CFR 146.89(a)(2)). Note that the UIC Program Director will evaluate the results and interpretations of MIT to independently assess the integrity of the injection wells.

Operational Testing and Monitoring During Injection

The Class VI Rule requires owners or operators to monitor injectate properties, injection rate, pressure, volume, corrosion of well materials, and perform pressure fall-off testing (40 CFR 146.90(a), (b), (c), and (f)), to indicate possible deviation from planned project operations, verify compliance with permit conditions, and to inform Area of Review (AoR) reevaluations. The results are expected to be interpreted with respect to regulatory requirements and past results. Note the UIC Program Director will evaluate the results to ensure that the composition of the injected stream is consistent with permit conditions and that it does not result in the injectate being classified as a hazardous waste.

Plume and Pressure-Front Tracking

The EPA (2013 EPA 816-R-13-001 – Testing and Monitoring Guidance) indicates that identification of the position of the injected CO_2 plume and the presence or absence of elevated pressure (i.e., the pressure front) are integral for verifying the storage reservoir is behaving as predicted, informing the reevaluation of the AoR, and protecting the USDWs. The temporal changes will be analyzed by comparing the new data to previously collected data, and time-series graphs will be developed and interpreted for each well, taking into consideration the injection rate and well location. Spatial patterns will also be analyzed by constructing maps that present contours of pressure and/or hydraulic head. Increases in pressure in wells above the confining zone may be indicative of fluid leakage. Increases in pressure within the injection zone will be compared to modeling predictions to determine whether the AoR is consistent with monitoring results. Pressure increases at a monitoring well location greater than predicted by the current site AoR model, or increases at a greater rate, may indicate that the model needs to be revised.

Geochemical Monitoring

The results of groundwater monitoring will be compared to baseline geochemical data collected during site characterization (40 CFR 146.82(a)(6)) to obtain evidence of fluid movement that may affect USDWs. The EPA (2013 EPA 816-R-13-001 – Testing and Monitoring Guidance) suggests that trends in groundwater concentrations may be indicative of fluid leakage—such as changes in total dissolved solids, major cations and anions, increasing CO_2 concentrations, decreasing pH, increasing concentration of injectate impurities, increasing concentration of leached constituents, and/or increased reservoir pressure and/or static water levels. The EPA also suggests that geochemical data be compared to results from rock-water-CO_2 experiments or geochemical modeling.

Note that the UIC Program Director will evaluate the groundwater monitoring data to independently assess data quality, constituent concentrations (including potential contaminants), and the resulting interpretation to determine if there are any indications of fluid leakage and/or plume migration and whether any action is necessary to protect USDWs (EPA 2013 EPA 816-R-13-001 – Testing and Monitoring Guidance).

A.7.2 Measurement Performance/Acceptance Criteria

The qualitative and quantitative design objective of the FutureGen CO_2 Pipeline and Storage Project's testing and monitoring activities is to monitor the performance of the storage reservoir relative to permit and USDW protection requirements. The design of these activities is intended to provide reasonable assurance that decision errors regarding compliance with the permit and/or protection of the USDW are unlikely. In accordance with EPA 2013 EPA 816-R-13-001 – Testing and Monitoring Guidance, the well testing and monitoring program includes operational CO_2 injection stream monitoring, well MIT, geochemical and indicator parameter monitoring of both the reservoir and lowermost USDWs, and indirect geophysical monitoring. Table A.5 lists the field and laboratory analytical parameters, methods, and performance criteria for CO_2 injection stream monitoring. Table A.6 shows the MIT parameters, methods, and performance criteria. Table A.7 lists the groundwater geochemical and indicator parameters, methods, and performance criteria. Table A.8 lists the performance criteria for continuously recorded parameter measurements. Table A.9 lists the indirect geophysical parameters, methods, and performance criteria.

Table A.5. CO_2 Injectate Monitoring Requirements

Analytical Parameter	Analytical Method #	Detection Limit or (Range)	Typical Precision/Accuracy	QC Requirements
Pressure	Analog gauges, pressure transmitters	0-2500 psi	Accuracy: ±0.065% of span	CO_2 Pressure Transmitter, Mfg: Rosemount Part No: 3051TG4A2B21AS5M5Q4
Temperature	Thermocouples, or resistance temperature detectors	0-150 °F	Accuracy: ±0.03% of span	CO_2 Temperature Transmitter Mfg: Rosemount Part No: 644HANAXAJ6M5F6Q4
Flow	Coriolis mass meter	Range spanning maximum anticipated injection rate per well	±0.5 %	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.
CO_2	GC/TCD	0.1-100%	± 10%	Replicate analyses within 10% of each other
O_2	GC/TCD	0.1-100%	± 10%	Replicate analyses within 10% of each other
Total sulfur	ISBT 14.0 (GC/SCD)	0.01 µL/L to 50 µL/L (ppmv) dilution dependent	± 10%	Daily blank, daily standard within 10% of calibration, secondary standard after calibration
Arsenic	ICP-MS, EPA Method 6020	1 ng/m³ (filtered volume)	±10%	Daily calibration
Selenium	ICP-MS, EPA Method 6020	5 ng/m³ (filtered volume)	±10%	Daily calibration
Mercury (Hg)	Cold vapor atomic absorption (CVAA)	0.25 µg/m³	± 10%	Daily calibration
H_2S	ISBT 14.0 (GC/SCD)	0.01 µL/L to 50 µL/L (ppmv) dilution dependent	± 10%	Daily blank, daily standard within 10% of calibration, secondary standard after calibration
Ar	GC/TCD	0.1-100%	± 10%	Replicate analyses within 10% of each other
Water vapor (moisture)	GC/HID*	< 100 ppm	± 10%	Replicate analyses within 10% of each other

GC/TCD – gas chromatography with a thermal conductivity detector
ISBT – International Society of Beverage Technologists
GC/SCD – gas chromatography with a sulfur chemiluminescence detector
GC/HID - gas chromatography with helium Ionization detector
* Andrawes (1983) or equivalent. Method subject to change in subsequent revisions.

Table A.6. Mechanical Integrity Testing and Corrosion Requirements

Analytical Parameter	Analytical Method #	QC Requirements
Corrosion of Well Tubulars		
Corrosion of well casing and tubing	Corrosion coupon monitoring (visual, weight, and size); U.S. EPA SW846 Method 1110A – "Corrosivity Toward Steel" (or a similar standard method).	Proper preparation of coupons per ASTM G1-03, Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens. Refer to SW846 Method 1110A for measurement QC requirements.
Corrosion of well casing (internal radius, wall thickness, general corrosion, pitting, and perforations)	Wireline logging (mechanical, ultrasonic, electromagnetic); casing evaluation would only be done during well workovers that require removal of tubing string.	Vendor calibration of well logging tool(s) per manufacturer recommendations.
Well cement corrosion (quality of cement bond to pipe, and channels in cement)	Wireline logging (acoustic, ultrasonic); casing evaluation would only be done during well workovers that require removal of tubing string.	Baseline cement evaluation logs prior to start of injection. Vendor calibration of well logging tool(s) per manufacturer recommendations
External Mechanical Integrity		
Temperature adjacent to the well	Temperature logging to identify fluid movement adjacent to well bore	Baseline temperature log prior to start of injection. Vendor calibration of well logging tool(s) per manufacturer recommendations
Fluid composition adjacent to the well; fluid movement	Pulsed-neutron logging in oxygen activation mode and thermal capture cross-section (sigma) mode	Baseline log prior to start of injection. Tool calibration per manufacturer recommendations
Internal Mechanical Integrity		
Continuous measurement of fluid pressure and fluid volume in annulus between tubing and long casing string during injection	Pressure and fluid volumes will be measured and logged automatically using electronic pressure sensors and fluid level indicators that are incorporated into the annulus pressurization system (APS).	Initial and ongoing calibration of pressure and fluid level sensors will be done as part of the Annulus Pressurization System Operations and Maintenance program.
Initial annulus pressure test prior to start of injection and following workovers that involve removing tubing and/or packer.	Annular pressure test per EPA UIC requirements	
Pressure Fall-Off Testing		
Well pressure; CO_2 injection rate-history.	Pressure transient analysis methods will be used to analyze pressure fall-off test data to assess well condition (skin) that could indicate need for well rehabilitation.	Initial and ongoing calibration of in-well pressure sensors. Initial and ongoing calibration (proving) of CO_2 flow-rate meters.

Table A.7. Groundwater Geochemical and Indicator Parameter 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-AES, EPA Method 6010B or similar	1 to 80 µg/L (analyte dependent)	±10%	Daily calibration; blanks, LCS, and duplicates and matrix spikes at 10% level per batch of 20
Trace Metals: Sb, As, Cd, Cr, Cu, Pb, Se, Tl	ICP-MS, EPA Method 6020 or similar	0.1 to 2 µg/L (analyte dependent)	±10%	Daily calibration; blanks, LCS, and duplicates and matrix spikes at 10% level per batch of 20
Cyanide (CN-)	SW846 9012A/B	5 µg/L	±10%	Daily calibration; blanks, LCS, and duplicates at 10% level per batch of 20
Mercury	CVAA SW846 7470A	0.2 µg/L	±20%	Daily calibration; blanks, LCS, and duplicates and matrix spikes at 10% level per batch of 20
Anions: Cl^-, Br^-, F^-, SO_4^{2-}, NO_3^-	Ion Chromatography, EPA Method 300.0A or similar	33 to 133 µg/L (analyte dependent)	±10%	Daily calibration; blanks, LCS, and duplicates at 10% level per batch of 20
Total and Bicarbonate Alkalinity (as $CaCO_3^{2-}$)	Titration, Standard Methods 2320B	1 mg/L	±10%	Daily calibration; blanks, LCS, and duplicates at 10% level per batch of 20
Gravimetric Total Dissolved Solids (TDS)	Gravimetric Method Standard Methods 2540C	10 mg/L	±10%	Balance calibration, duplicate samples
Water Density	ASTM D5057	0.01 g/mL	±10%	Balance calibration, duplicate samples
Total Inorganic Carbon (TIC)	SW846 9060A or equivalent Carbon analyzer, phosphoric acid digestion of TIC	0.2 mg/L	±20%	Quadruplicate analyses, daily calibration
Dissolved Inorganic Carbon (DIC)	SW846 9060A or equivalent Carbon analyzer, phosphoric acid digestion of DIC	0.2 mg/L	±20%	Quadruplicate analyses, daily calibration
Total Organic Carbon (TOC)	SW846 9060A or equivalent Total organic carbon is converted to carbon dioxide by chemical oxidation of the organic carbon in the sample. The carbon dioxide is measured using a non-dispersive infrared detector.	0.2 mg/L	±20%	Quadruplicate analyses, daily calibration
Dissolved Organic Carbon (DOC)	SW846 9060A or equivalent Total organic carbon is converted to carbon dioxide by chemical oxidation of the organic carbon in the sample. The carbon dioxide is measured using a non-dispersive infrared detector.	0.2 mg/L	±20%	Quadruplicate analyses, daily calibration
Volatile Organic Analysis (VOA)	SW846 8260B or equivalent Purge and Trap GC/MS	0.3 to 15 µg/L	±20%	Blanks, LCS, spike, spike 1 duplicate per batch of 20
Methane	RSK 175 Mod Headspace GC/FID	10 µg/L	±20%	Blanks, LCS, spike, spike 1 duplicate per batch of 20
Stable Carbon Isotopes $^{13/12}C$ ($\delta^{13}C$) of DIC in Water	Gas Bench for $^{13/12}C$	50 ppm of DIC	±0.2p	Duplicates and working standards at 10%

Table A.7. (contd)

Parameter	Analysis Method	Detection Limit or Range	Typical Precision/ Accuracy	QC Requirements
Radiocarbon ^{14}C of DIC in Water	AMS for ^{14}C	Range: 0 to 200 pMC	±0.5 pMC	Duplicates and working standards at 10%
Hydrogen and Oxygen Isotopes $^{2/1}H$ (δ) and $^{18/16}O$ (^{18}O) of Water	CRDS H_2O Laser	Range: -500‰ to 200‰ vs. VSMOW	$^{2/1}H$: ±2.0‰ $^{18/16}O$: ±0.3‰	Duplicates and working standards at 10%
Carbon and Hydrogen Isotopes (^{14}C, $^{13/12}C$, $^{2/1}H$) of Dissolved Methane in Water	Offline Prep & Dual Inlet IRMS for ^{13}C; AMS for ^{14}C	^{14}C Range: 0 & DupMC	^{14}C: ±0.5pMC ^{13}C: ±0.2‰ $^{2/1}H$: ±4.0‰	Duplicates and working standards at 10%
Compositional Analysis of Dissolved Gas in Water (including N_2, CO_2, O_2, Ar, H_2, He, CH_4, C_2H_6, C_3H_8, iC_4H_{10}, nC_4H_{10}, iC_5H_{12}, nC_5H_{12}, and C_6+)	Modified ASTM 1945D	1 to 100 ppm (analyte dependent)	Varies by component	Duplicates and working standards at 10%
Radon (^{222}Rn)	Liquid scintillation after pre-concentration	5 mBq/L	±10%	Triplicate analyses
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

ICP-AES = inductively coupled plasma atomic emission spectrometry; ICP-MS = inductively coupled plasma mass spectrometry; LCS = laboratory control sample; GC/MS = gas chromatography–mass spectrometry; GC/FID = gas chromatography with flame ionization detector; AMS = accelerator mass spectrometry; CRDS = cavity ring down spectrometry; IRMS = isotope ratio mass spectrometry; LC-MS = liquid chromatography-mass spectrometry; ECD = electron capture detector

Table A.8. Required Minimum Specifications for Real-Time Parameter Measurements

Parameter	Range	Resolution	Accuracy	Additional Requirements
Pressure	0 – 2000 psi	0.05 psi	±2 psi	Calibration per manufacturer recommendations
Temperature	50 – 120 °F	0.1 °F	±2 °F	Calibration per manufacturer recommendations
Specific Conductance	0 – 85 mS/cm	0.002 mS/cm	±0.01 mS/cm	Calibration during sampling events

Table A.9. Indirect Geophysical Monitoring Requirements

Analytical Parameter	Analytical Method #	Detection Limit or (Range)	Typical Precision/Accuracy	QC Requirements
Sigma neutron capture cross section	PNC	Dependent on formation and well completion. Salinity >40 Kppm; porosity >0.10	0.5 c.u.	Manufacturer calibration and periodic recalibration
Carbon/Oxygen inelastic	PNC	Dependent on formation and well completion. Porosity >0.15;	Dependent on log time. Requires slow (5–8 ft/min) logging speed	Manufacturer calibration and periodic recalibration
Temperature	Temperature logging	0-350 °F	0.2 °F	Manufacturer calibration and periodic recalibration
Gamma	Gamma-ray logging	NA	1 count/API	Manufacturer calibration and periodic recalibration
Velocity	Passive seismic: geophone	145 dB; 1–350 Hz	10^{-7} m/s	Manufacturer calibration and periodic recalibration
Velocity	Passive seismic: seismometer	165dB ; 0.01–150 Hz	10^{-9} m/s	Manufacturer calibration and periodic recalibration
Acceleration	Passive seismic: force balance accelerometer	155 dB; DC-200 Hz	10^{-6} m/s^2	Manufacturer calibration and periodic recalibration
Acceleration	Passive seismic: fiber-optic accelerometer	0.01–2000 Hz	$< 5.\ 10^{-7}$ m/s^2 / √Hz	Manufacturer calibration
Position	Integrated deformation: GPS	NA	5 mm+1 ppm horiz.; 10 mm +1 ppm vert.	Manufacturer calibration and periodic recalibration
Deformation	Integrated deformation: DInSAR	NA	<10 mm	Space Agency calibration
Acceleration	Time-lapse gravity	NA	10^{-8} m/s^2 (10^{-6} Gal)	Manufacturer calibration and periodic recalibration

A.8 Special Training/Certifications

Wireline logging, indirect geophysical methods, and some non-routine sampling will be performed by trained, qualified, and certified personnel, according to the service company's requirements. The subsequent data will be processed and analyzed according to industry standards (Appendix A).

Routine injectate and groundwater sampling will be performed by trained personnel; no specialized certifications are required. Some special training will be required for project personal, particularly in the areas of PNC logging, certain geophysical methods, certain data-acquisition/transmission systems, and certain sampling technologies.

Training of project staff will be conducted by existing project personnel knowledgeable in project-specific sampling procedures. Training documentation will be maintained as project QA records.

A.9 Documentation and Records

The Class VI Rule requires that the owner or operator submit the results of testing and monitoring as part of the required semi-annual reports (40 CFR 146.91(a)(7)). These reports will follow the format and content requirement specified in the final permit, including required electronic data formats.

All data are managed according to the Project Data Management Plan (Bryce et al. 2013). All project records are managed according to the project records management requirements. All data and project records will be stored electronically on secure servers and routinely backed-up.

The FutureGen CO_2 Pipeline and Storage Facility PM (assisted by the QEngineer) will be responsible for ensuring that all affected project staff (as identified in the distribution list) have access to the current version of the approved QASP.

B. Data Generation and Acquisition

The primary goal of testing and monitoring activities is to verify that the Morgan County carbon dioxide (CO_2) storage site is operating as permitted and is not endangering any underground sources of drinking water (USDWs). To this end, the primary objectives of the testing and monitoring program are to track the lateral extent of supercritical carbon dioxide ($scCO_2$) within the target reservoir; characterize any geochemical or geomechanical changes that occur within the reservoir, caprock, and overlying aquifers; monitor any change in land-surface elevation associated with CO_2 injection; determine whether the injected CO_2 is effectively contained within the reservoir; and detect any adverse impact on USDWs.

This element of the Quality Assurance and Surveillance Plan (QASP) addresses data-generation and data-management activities, including experimental design, sampling methods, sample handling and custody, analytical methods, quality controls, and instrumentation/equipment specific to each testing and monitoring method. It should be noted that not all of these QASP aspects are applicable to all testing and monitoring methods. Other QASP aspects, such as inspection/acceptance of supplies and consumables (Section B.12), non-direct measurements (e.g., existing data) (Section B.13), and data management (Section B.14), are applicable to all techniques and are discussed separately.

Well testing and monitoring activities are broken into eight main categories/subtasks, as listed below.

1. CO_2 Injection Stream Analysis – includes CO_2 injection stream gas sampling and chemical analyses. See Section B.1.
2. Continuous Recording of Injection Pressure, Rate, and Volume, and Annulus Pressure. See Section B.2.
3. Corrosion Monitoring – includes sampling and analysis of corrosion coupons. See Section B.3.
4. Groundwater Quality Monitoring – includes formation fluid sampling within the Ironton Sandstone (Above Confining Zone) and St. Peter Sandstone (lowermost USDW) and subsequent geochemical analyses, as well as continuous monitoring of indicator parameters. See Section B.4.
5. External Mechanical Integrity Testing – includes temperature logging and pulsed-neutron capture (PNC) logging (both gas-view and oxygen-activation mode), as well as cement-evaluation and casing inspection logging. See Section B.5.
6. Pressure Fall-Off Testing. See Section B.6.
7. Direct CO_2 Plume and Pressure-Front Tracking – includes all formation fluid sampling within the Mount Simon Sandstone, as well as continuous monitoring of pressure, temperature, and fluid specific conductance. See Section B.7.
8. Indirect CO_2 Plume and Pressure-Front Tracking – includes PNC logging, passive seismic monitoring, integrated deformation monitoring, and time-lapse gravity. Optional supplementary methods may include three-dimensional (3D) multicomponent surface seismic, and multicomponent vertical seismic profiling. See Sections B.8 through B.11.

B.1 Carbon Dioxide Stream Analysis

The Alliance will conduct injection stream analysis to meet the requirements of 40 CFR 146.90(a). This section describes the experimental design, sampling methods, sample handling and custody, analytical methods, quality controls, and instrumentation/equipment specific to CO_2 stream analysis monitoring activities. Refer to Sections B.12 through B.14 for general descriptions of material inspection/acceptance methods, non-direct measurements (e.g., existing data), and data management.

B.1.1 Sampling Process Design (Experimental Design)

Based on the anticipated composition of the CO_2 stream, a list of parameters has been identified for analysis. Samples of the CO_2 stream will be collected regularly (e.g., quarterly) for chemical analysis.

Table B.1. Parameters and Frequency for CO_2 Stream Analysis

Parameter/Analyte	Frequency
Pressure	Continuous
Temperature	Continuous
CO_2 (%)	quarterly
Water (lb/mmscf)	quarterly
Oxygen (ppm)	quarterly
Sulfur (ppm)	quarterly
Arsenic (ppm)	quarterly
Selenium (ppm)	quarterly
Mercury (ppm)	quarterly
Argon (%)	quarterly
Hydrogen Sulfide (ppm)	quarterly

B.1.2 Sampling Methods

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 collected in the gas state rather than as 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.

B.1.3 Sample Handling and Custody

Samples will be transported to the Monitoring, Verification, and Accounting (MVA) laboratory space in the control building for processing, packaging, and shipment to the contracted laboratory, following standard sample handling and chain-of-custody guidance (EPA 540-R-09-03, or equivalent).

B.1.4 Analytical Methods

Analytical methods are listed in Table A.5

B.1.5 Quality Control

A wide variety of monitoring data will be collected specifically for this project, under appropriate quality assurance (QA) protocols. Data QA and surveillance protocols will be designed to facilitate compliance with requirements specified in 40 CFR 146.90(k).

B.1.6 Instrument/Equipment Testing, Inspection, and Maintenance

For sampling, field equipment will be maintained, serviced, and calibrated per manufacturers' recommendations. Spare parts that may be needed during sampling will be included in supplies on-hand during field sampling.

For all laboratory equipment, testing, inspection, and maintenance will be the responsibility of the analytical laboratory per method-specific protocols and the laboratory's QA program, which will be reviewed by the Alliance prior to contract award.

B.1.7 Instrument/Equipment Calibration and Frequency

Calibration of all laboratory instrumentation/equipment will be the responsibility of the analytical laboratory per method-specific protocols and the laboratory's QA program, which will be reviewed by the Alliance prior to contract award.

B.2 Continuous Recording of Injection Pressure, Rate, Volume, and Annulus Pressure

This section describes the experimental design, sampling methods, sample handling and custody, analytical methods, quality controls, and instrumentation/equipment specific to continuous monitoring of injection parameters. Refer to Sections B.12 through B.14 for general descriptions of material inspection/acceptance methods, non-direct measurements (e.g., existing data), and data management.

B.2.1 Sampling Process Design (Experimental Design)

The Alliance will conduct continuous monitoring of injection parameters to meet the requirements of 40 CFR 146.90(b). These activities include continuous recording of injection pressure, temperature, flow rate, and volume, as well as the annulus pressure.

B.2.2 Sampling Methods

Continuous Recording of Injection Pressure and Temperature

An electronic P/T gauge will be installed on the outside of the tubing string, approximately 30 ft above the packer, and ported into the tubing to continuously measure CO_2 injection P/T inside the tubing at this depth. Mechanical strain gauges and thermocouples will be the primary monitoring devices for pressure and temperature.

Injection P/T will also be continuously measured at the surface via real-time P/T instruments installed in the CO_2 pipeline near the pipeline interface with the wellhead. The P/T of the injected CO_2 will be continuously measured for each well. The pressure will be measured by electronic pressure transmitter with analog output mounted on the CO_2 line associated with each injection well. The temperature will be measured by an electronic temperature transmitter mounted in the CO_2 line at a location near the pressure transmitter, and both transmitters will be located near the wellhead. The transmitters will be connected to the Annulus Pressurization System (APS) programmable logic controller (PLC) located in the Control Building adjacent to the injection well pad.

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 flow meters will be connected to the main CO_2 storage site SCADA system for continuous monitoring and control of the CO_2 injection rate into each well. 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 fourth well receiving the balance of the total flow rate.

B.2.3 Sample Handling and Custody

No specialized sample/data handling procedures are required. Electronic sensor data (e.g., pressure data) will be networked through the local-area fiber-optic network using Ethernet network interfaces back to data-acquisition systems located in the MVA data center.

Electronic data and field records will be transferred to laptop and/or desktop computers and/or backed-up on secured servers at least quarterly, as well as scanned copies of all pertinent hardcopy field records/notes.

B.2.4 Analytical Methods

Continuously recorded injection parameters will be reviewed and interpreted on a regular basis, to evaluate the injection stream parameters against permit requirements. Trend analysis will also help evaluate the performance (e.g., drift) of the instruments, suggesting the need for maintenance or calibration.

B.2.5 Quality Control

Continuous monitoring equipment will be calibrated according to the manufacturers' recommendations. If trends or other unexplained variability in the data are observed that might indicate a suspect response, instruments will be evaluated and, if required, recalibrated or replaced.

B.2.6 Instrument/Equipment Testing, Inspection, and Maintenance

The surface instruments will be maintained according to manufacturers' recommendations; however, if data trends indicate a suspect response, instruments will be evaluated and, if required, recalibrated or replaced.

B.2.7 Instrument/Equipment Calibration and Frequency

Because the bottom-hole P/T gauge will be attached to the tubing string, the gauge will be recalibrated or replaced only when the injection well tubing string is pulled, which would occur only if warranted by a downhole issue that can only be addressed by performing a well workover. The surface P/T instruments will be calibrated according to manufacturers' recommendations.

B.3 Corrosion Monitoring

This section describes the experimental design, sampling methods, sample handling and custody, analytical methods, quality controls, and instrumentation/equipment specific to corrosion-monitoring activities. Refer to Sections B.12 through B.14 for general description of material inspection/acceptance methods, non-direct measurements (e.g., existing data), and data management.

B.3.1 Sampling Process Design (Experimental Design)

The Alliance will conduct corrosion monitoring of well materials to meet the requirements of 40 CFR 146.90(c). Corrosion-monitoring activities are designed to monitor the integrity of the injection wells throughout the operational period. This includes using corrosion coupons as well as periodic cement-evaluation and casing inspection logs when tubing is removed from the well (i.e., during well workovers). Corrosion coupons will be made of the same materials as the long string of casing and the injection tubing, and will be placed in the CO_2 pipeline for ease of access.

B.3.2 Sampling Methods

Corrosion monitoring will include corrosion coupons as well as periodic cement-evaluation and casing inspection logs.

Corrosion Coupon Monitoring

Corrosion coupons will be made of the same material as the long string of casing and the injection tubing and placed in the CO_2 injection pipeline. The coupons will be removed quarterly and assessed for corrosion using the ASTM International (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. The corrosion rate will be calculated as the weight loss during the exposure period divided by the duration (i.e., weight loss method).

Cement-evaluation and Casing Inspection Logging

Cement-evaluation and casing inspection logs will be run periodically, on an opportunistic basis, whenever tubing is removed from the well (i.e., during well workovers). See Section B.5 on external mechanical integrity testing.

B.3.3 Sample Handling and Custody

Corrosion monitoring will include corrosion coupons as well as periodic cement-evaluation and casing inspection logs. No specialized sample handling or chain-of-custody procedures are needed. The coupons will be removed from the pipeline, then taken to the nearby mobile lab (field trailer) where they will be cleaned, inspected, weighed, and measured. They will be immediately returned to the pipeline. Cement-evaluation and casing inspection log data will be handled using best management practices. See Section B.5 on external mechanical integrity testing.

B.3.4 Analytical Methods

The corrosion coupons will be cleaned, inspected visually for evidence of corrosion (e.g., pitting), weighed, and measured each time they are removed (ASTM G1-03, Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens). The corrosion rate will be calculated as the weight loss during the exposure period divided by the duration (i.e., weight loss method).

See Section B.5 on external mechanical integrity testing for cement-evaluation and casing inspection logging analytical methods.

B.3.5 Quality Control

Two groups of four replicate corrosion coupons of each material type will be placed in proximity to each other within two different locations within the CO_2 injection pipeline. A third group of four replicate samples of each material type will placed in proximity to each other within a simulated injection pipeline as a control (not exposed to CO_2). All samples will be removed quarterly and subjected to the same visual and measurement methodologies. This approach will allow an evaluation of the potential spatial variability in corrosion rates within the injection tubing, as well as the natural variability between coupon samples. Corrosion rates (calculated as the weight loss during the exposure period divided by the duration, i.e., weight loss method) and statistical analyses (e.g., t-test) will be independently reviewed and documented.

See Section B.5 on external mechanical integrity testing for cement-evaluation and casing inspection logging quality control methods.

B.3.6 Instrument/Equipment Testing, Inspection, and Maintenance

Equipment and instrumentation for visual inspection and measurement of the corrosion coupons will consist of materials to clean corrosion products off the coupons as well as equipment and instrumentation for visual inspection and measurement in accordance with ASTM G1-03. Key inspection and measurement equipment may include calipers, an analytical balance (e.g., electronic scale), and a low-power microscope or hand lens (e.g., 7X to 30X). The analytical balance should be able to measure to with + or -0.2 to 0.02 mg. Calipers should be able to measure to about 1% of the area measured (ASTM G1-03).

Maintenance (e.g., charging, batteries, etc.) and instrument checks will be performed quarterly, prior to each sampling event. All equipment and materials will be visually inspected for damage, calibration dates, battery life, etc. prior to use. Fresh batteries and backup equipment/instrumentation will be stored in the mobile lab/field trailer.

See Section B.5 on external mechanical integrity testing for instrumentation and equipment testing, inspection, and maintenance relative to cement-evaluation and casing inspection logging.

B.3.7 Instrument/Equipment Calibration and Frequency

Calipers, analytical balances, and other measuring and testing instrumentation will be calibrated by the manufacturer, according to its recommended procedures and frequencies. See Section B.5 on external mechanical integrity testing for instrumentation and equipment calibration relative to cement-evaluation and casing inspection logging.

B.4 Groundwater Quality Monitoring (ACZ and USDW wells)

This section describes the experimental design, sampling methods, sample handling and custody, analytical methods, quality controls, and instrumentation/equipment specific to groundwater quality monitoring activities. Refer to Sections B.12 through B.14 for general description of material inspection/acceptance methods, non-direct measurements (e.g., existing data), and data management.

B.4.1 Sampling Process Design (Experimental Design)

The Alliance will conduct ground-water-quality/geochemical monitoring above the confining zone to meet the requirements of 40 CFR 146.90(d).

The planned groundwater quality monitoring well network layout, number of wells, well design, and sampling regimen are based upon site-specific characterization data, and consider structural dip, the locations of existing wells, expected ambient flow conditions, and the potential for heterogeneities or horizontal/vertical anisotropy within the overburden materials (see also Section A.6.2). The planned monitoring network consists of two wells within the first permeable interval immediately above the primary confining zone (Ironton Sandstone), and one well within the lowermost USDW (St. Peter Sandstone) (Figure A.3). The above confining zone (ACZ) wells will be completed in the Ironton Sandstone and monitor for changes in pressure, groundwater chemistry, indicator parameters, and microseismicity. The ACZ monitoring interval is located immediately above the primary confining zone. One of these wells will be located ~1,000 ft west of the injection site adjacent to the western injection lateral; the other will be located ~1,500 ft west of the western injection lateral terminus. The USDW well (USDW1) will be installed at the base of the St. Peter Sandstone to monitor the groundwater quality of the lowermost USDW.

The Alliance plans to conduct periodic fluid sampling as well as continuous pressure, temperature, and specific conductance (P/T/SpC) monitoring throughout the injection phase in the two ACZ monitoring wells and the USDW well. (Table A.3 lists the parameters and instrumentation that will be used at each of the ACZ and USDW monitoring wells. Minimum specifications for the planned continuous measurements are listed in Table A.8.)

The Alliance will also conduct baseline surficial aquifer sampling in the shallow, semi-consolidated glacial sediments, using approximately nine local landowner wells and one well drilled for the project. Because near-surface environmental impacts are not expected, surficial aquifer (<100 ft bgs) monitoring will only be conducted for a sufficient duration to establish baseline conditions (minimum of three sampling events). Surficial aquifer monitoring is not planned during the injection phase; however, the need for additional surficial aquifer monitoring will be continually evaluated throughout the operational phases of the project, and may be reinstituted if conditions warrant.

B.4.2 Sampling Methods

Fluid samples will be collected at monitored formation depths and maintained at formation pressures within a closed pressurized sample container to prevent the escape of dissolved gases. Access to the monitored intervals at the ACZ and USDW monitoring wells will be through the 5-1/2-in. casing that is cemented into the borehole.

Aqueous samples will be collected from each monitoring well, initially on a quarterly basis and later less frequently, to determine the concentration of CO_2 and other constituents in the monitoring interval fluids. The fluid samples will be collected within the open interval of each monitoring well using a flow-through sampler with a 950-cc (or larger) sample chamber. The samples will be maintained at formation pressure within a closed sample container to prevent the escape of dissolved gases. Prior to sampling, the P/T/SpC probe will be monitored as the well is purged (up to three times the volume of the well-screen section will be discharged from the well before collecting the sample). The probe will then be removed from the well and the sampler will be run into the borehole on the same wireline cable to collect the pressurized fluid sample. Additional purging may be conducted just prior to collection of the pressurized fluid sample if mixing between the fluid column and sampling interval during insertion of the sampler is a concern.

B.4.3 Sample Handling and Custody

After removing the sampler from the well, the closed and pressurized sample container(s) will be transported to the MVA laboratory space in the control building for processing following standard chain-of-custody procedures.

B.4.4 Analytical Methods

The analytical methods for groundwater quality monitoring in the ACZ and USDW wells are summarized in Table A.7.. Where possible, methods are based on standard protocols from EPA or Standard Methods for the Examination of Water and Wastewater (American Public Health Association, American Water Works Association, Water Environment Federation, 19th edition or later, Washington, D.C.). Laboratories shall have standard operating procedures for the analytical methods performed.

B.4.5 Quality Control

The quality control (QC) elements in this section are used to help evaluate whether groundwater samples are free of contamination and whether the laboratories performed the analyses within acceptable accuracy and precision requirements. Several types of field and laboratory QC samples are used to assess and enhance data quality (Table B.2)

Table B.2. Quality Control Samples

	Field QC	
Sample Type	Primary Characteristic Evaluated	Frequency
Trip Blank	Contamination from containers or transportation	1 per sampling event
Field Duplicates	Reproducibility	1 per sampling event
	Laboratory QC	
Sample Type	Primary Characteristic Evaluated	Frequency
Method Blank	Laboratory contamination	1 per batch
Lab Duplicate	Laboratory reproducibility	(a)
Matrix Spike	Matrix effects and laboratory accuracy	(a)
Matrix Spike Duplicate	Laboratory reproducibility/accuracy	(a)
Laboratory Control Sample	Method accuracy	1 per batch

(a) As defined in the laboratory contract and analysis procedures (typically 1 per 10 samples).

Field QC samples consist of trip blanks and duplicate samples. Trip blanks are preserved sample bottles that are filled with deionized water and transported unopened to the field in the same storage container that will be used for samples collected that day. Trip blanks evaluate bottle cleanliness, preservative purity, equipment decontamination, and proper storage and transport of samples. The frequency of collection for trip blanks is one per sampling event. Field duplicates are replicate samples that are collected at the same well. After each type of bottle is filled, a second, identical bottle is filled for each type of analysis. Both sets of samples are stored and transported together. Field duplicates provide information about sampling and analysis reproducibility. The collection frequency for field duplicates is one per sampling event.

Laboratory QC samples include method blanks, laboratory duplicates, matrix spikes, matrix spike duplicates, and laboratory control samples (defined below). These samples are generally required by EPA method protocols. Frequencies of analysis are specified in Table B.2 and in the laboratories' standard operating procedures.

- **Method blank** – an analyte-free matrix to which all reagents are added in the same volumes or proportions as used in sample processing. The method blank is carried through the complete preparation and analysis process. Method blanks are used to quantify contamination from the analytical process.
- **Laboratory duplicate** – an intra-laboratory split sample that is used to evaluate the precision of a method in a given sample matrix.
- **Matrix spike** – an aliquot of a sample that is spiked with a known concentration of target analytes(s). The matrix spike is used to assess the bias of a method in a given sample matrix. Spiking occurs prior to sample preparation and analysis.
- **Matrix spike duplicate** – a replicate spiked aliquot of a sample that is subjected to the entire sample preparation and analytical process. Matrix spike duplicate results are used to determine the bias and precision of a method in a given sample matrix.
- **Laboratory control sample** – a control matrix (typically deionized water) spiked with analytes representative of the target analytes or a certified reference material that is used to evaluate laboratory accuracy.

Besides these measures, the laboratories maintain internal QA programs and are subject to internal and external audits.

B.4.6 Instrument/Equipment Testing, Inspection, and Maintenance

For groundwater sampling, field equipment will be maintained, serviced, and calibrated according to the manufacturers' recommendations. Spare parts that may be needed during sampling will be included in supplies on-hand during field sampling.

For all laboratory equipment, testing, inspection, and maintenance will be the responsibility of the analytical laboratory according to method-specific protocols and the laboratory's QA program, which will be reviewed by the Alliance prior to contract award.

B.4.7 Instrument/Equipment Calibration and Frequency

Calibration of all laboratory instrumentation/equipment will be the responsibility of the analytical laboratory according to method-specific protocols and the laboratory's QA program, which will be reviewed by the Alliance prior to contract award.

B.5 External Mechanical Integrity Testing

This section describes the experimental design, sampling methods, sample handling and custody, analytical methods, quality controls, and instrumentation/equipment specific to external mechanical integrity testing (MIT) activities. Refer to Sections B.12 through B.14 for general descriptions of material inspection/acceptance methods, non-direct measurements (e.g., existing data), and data management.

B.5.1 Sampling Process Design (Experimental Design)

The Alliance will conduct external MIT to meet the requirements of 40 CFR 146.90(e). These tests are designed to include temperature logging, PNC logging, and cement-evaluation logging. An initial (baseline) temperature and PNC logs 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 PNC logs for evaluating external mechanical integrity.

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.

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 PNC 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 PNC 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 PNC 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.

In addition to oxygen activation logging, the PNC tool will also be run in thermal capture cross-section (sigma) mode to detect the presence of CO_2 outside the casing.

PNC logging will be the primary method used to evaluate the external mechanical integrity of the injection wells.

Cement-Evaluation Logging

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 that involve removing the tubing string). Some cement-evaluation logs are also capable of providing information about the condition of the casing string, such as wall thickness and inside diameter (e.g., Schlumberger isolation scanner tool).

B.5.2 Sampling Methods

PNC logging will be the primary method used to evaluate the external mechanical integrity of the injection wells (EPA requires annual MIT demonstrations). PNC and temperature logging will be conducted on an opportunistic basis, for example, when each well is taken out of service. Temperature and PNC logging will be performed through the tubing and therefore will not require removal of the tubing and packer from the well. However, the cement-evaluation and casing-evaluation logging will be conducted only when tubing is removed from the well as this cannot be performed through tubing.

B.5.3 Sample Handling and Custody

No specialized sample/data handling procedures are required. Logging data will be recorded on a computer located in the wireline logging truck. All electronic data and field records will be transferred to laptop and/or desktop computers and backed-up on secure servers at the conclusion of each logging event, as will scanned copies of all pertinent hardcopy field records/notes.

B.5.4 Analytical Methods

Wireline log data will be processed following industry best practices and coordinated with the borehole-logging operator to optimize data-collection parameters. Modeling can be done to simulate near-borehole interferences and remove their effects from the signal. Modeling is a recommended procedure and requires knowledge of the target formations and fluids that must be obtained from cores and additional logging data. Each logging result will be compared for each well to the baseline or previous survey, as applicable, to determine changes.

B.5.5 Quality Control

Verification of vendor processing software and results will ensure that the acquired data are acceptable and are reproducible. Third-party logging and processing for a subset of boreholes and logging events can be used as part of the validation procedure. Failure of tool performance in the field or unreproducible "repeat sections" will result in non-acceptance of the data, and may trigger a return of the wireline tool to the manufacturer for recalibration or replacement. Off-normal results/comparisons to baseline will trigger additional evaluation and possible new logging runs.

B.5.6 Instrument/Equipment Testing, Inspection, and Maintenance

Examples of industry-published guidelines for calibration and field operation of the pulsed-neutron capture (PNC) wireline log hardware and data-collection software are provided in Appendix A.

B.5.7 Instrument/Equipment Calibration and Frequency

To ensure data acquisition quality, each logging tool will be calibrated for accuracy, checked to be in good working order, and verified by the manufacturer. All tools and field operation software will be provided by the manufacturer with an auditable verification record to ensure traceability. In addition to the initial manufacturer calibration, tool recalibration will be performed monthly and both prior to and after each logging event following the manufacturer's guidelines. Examples of industry-published guidelines for calibration and field operation of wireline log hardware and data-collection software are provided in Appendix B.

B.6 Pressure Fall-Off Testing

This section describes the experimental design, sampling methods, sample handling and custody, analytical methods, quality controls, and instrumentation/equipment specific to pressure fall-off testing activities. Refer to Sections B.12 through B.14 for general descriptions of material inspection/acceptance methods, non-direct measurements (e.g., existing data), and data management.

B.6.1 Sampling Process Design (Experimental Design)

Pressure fall-off testing will be conducted upon completion of the injection wells to characterize reservoir hydrogeologic properties and aquifer response model characteristics (e.g., nonleaky vs. leaky reservoir; homogeneous vs. fractured media) as well as changes in near-well/reservoir conditions that may affect operational CO_2 injection behavior in accordance with 40 CFR 146.87(e)(1). Pressure fall-off testing will also be conducted at least once every five (5) years after injection operations begin, or more frequently if required by the UIC Program Director (40 CFR 146.90 (f)). Specifically, the objective of the periodic pressure fall-off testing is to determine whether any significant changes in the near-wellbore conditions have occurred that may adversely affect well/reservoir performance (e.g., well injectivity, anomalous reservoir pressure behavior). Detailed descriptions for conducting and analyzing pressure fall-off tests are provided by the EPA (2002, 2003, and 2012). These guidelines will be followed when conducting pressure fall-off tests for the FutureGen 2.0 CO_2 Pipeline and Storage Project.

B.6.2 Sampling Methods

Controlled pressure fall-off tests are conducted by terminating injection for a designed period/duration of time. The pressure fall-off test is initiated by terminating injection, shutting-in the well by closing the surface wellhead valve(s), and maintaining continuous monitoring the surface and downhole pressure recovery within the well/test interval system during the fall-off/recovery period. The designed duration of the pressure fall-off recovery test is a function of a number of factors, including the exhibited pre-operational injection reservoir test response characteristics, the injection well history prior to termination (i.e., injection duration, rate history), and potential pressure interference effects imposed by any surrounding injection wells completed within the same reservoir. Because of the potential impact of injection-rate variability on early-time pressure fall-off recovery behavior, the EPA (2012) recommends that injection rates and pressures be uniform and held relatively constant prior to initiating a pressure fall-off test.

Upon shutting-in the well, in-well pressure measurements are monitored continuously in real time, both downhole (within or in proximity to the injection reservoir) and at the surface wellhead location. The EPA (2012) recommends the use of two pressure probes at each location, with one serving as a verification source and the other as a backup/replacement sensor if the primary pressure transducer becomes unreliable or inoperative. The duration of the shut-in period used in conducting the pressure fall-off test should be extended sufficiently beyond wellbore storage effects and when the pressure recovery is indicative of infinite-acting radial flow (IARF) conditions. The establishment of IARF conditions is best determined by using pressure derivative diagnostic analysis plots (Bourdet et al. 1989; Spane 1993; Spane and Wurstner 1993), and is indicated when the log-log pressure derivative/recovery time plot, plots as a horizontal line. When IARF pressure fall-off conditions are indicated, the pressure response vs. log of fall-off/recovery time plots as a straight line on a standard semi-log plot. The EPA (2012) recommends a general rule-of-thumb of extending pressure fall-off tests a factor of three to five beyond the time required to reach radial flow conditions, while Earlougher (1977) suggests extending recovery periods between 1 to 1.5 log cycles beyond when the pressure response starts to deviate from purely wellbore storage response characteristics (i.e., a unit slope, 1:1 on a standard log-log pressure fall-off recovery plot).

For projects like FutureGen 2.0 that will use multiple injection wells completed within the same reservoir zone, the EPA (2012) recommends special considerations to be used for pressure fall-off testing to minimize the pressure response impacts from neighboring injection wells on the pressure fall-off test well recovery response. For the neighboring injection wells (i.e., those not being tested), the EPA (2012) recommends that injection at these wells either should be terminated prior to initiating the pressure fall-off test for a duration exceeding the planned shut-in period, or that injection rates at the neighboring injection wells be held constant and continuously recorded prior to and during the fall-off recovery test. After completion of the fall-off test, additional large-scale areal reservoir hydraulic/storativity characterization information may be derived for the injection reservoir by implementing a stepped-pulse pressure interference signal (by significantly increasing and/or decreasing injection rates) initiated from the neighboring injection wells. The arrival of the observed pulsed pressure signal at the fall-off test well provides information (i.e., due to arrival time and attenuation of the pressure pulse signal) about inter-well reservoir conditions (e.g., hydraulic diffusivity, directional lateral extent of injected CO_2), particularly if compared to pre-injection interference test response characteristics.

B.6.3 Sample Handling and Custody

No specialized sample/data handling procedures are required. Electronic sensor data (e.g., pressure data) will be recorded on data loggers. All electronic data and field records will be transferred to laptop and/or desktop computers and backed-up on secure servers at the conclusion of each test, as well as scanned copies of all pertinent hardcopy field records/notes.

B.6.4 Analytical Methods

Quantitative analysis of the pressure fall-off test response recorded following termination of injection for the test well provides the basis for assessing near well and larger-scale reservoir behavior. Comparison of diagnostic pressure fall-off plots established prior to operational injection of CO_2 and periodic fall-off tests conducted during operational injection phases can be used to determine whether significant changes in well or injection reservoir conditions have occurred. Diagnostic derivative plot analysis (Bourdet et al. 1989; Spane 1993; Spane and Wurstner 1993) of the pressure fall-off recovery response is particularly useful for assessing potential changes in well and reservoir behavior.

The EPA (2002, 2003) provides a detailed discussion on the use of standard semi-log and log-log diagnostic and analysis procedures for pressure fall-off test interpretation. The plotting of downhole temperature concurrent with the observed fall-off test pressure is also useful diagnostically for assessing any observed anomalous pressure fall-off recovery response. Commercially available pressure gauges typically are self-compensating for environmental temperature effects within the probe sensor (i.e., within the pressure sensor housing). However, as noted by the EPA (2012), if temperature anomalies are not accounted for correctly (e.g., well/reservoir temperatures responding differently than registered within the probe sensor), erroneous fall-off pressure response results maybe be derived. As previously discussed, concurrent plotting of downhole temperature and pressure fall-off responses is commonly useful for assessing when temperature anomalies may be affecting pressure fall-off/recovery behavior. In addition, diagnostic pressure fall-off plots should be evaluated relative to the sensitivity of the pressure gauges used to confirm adequate gauge resolution (i.e., excessive instrument noise).

Standard diagnostic log-log and semi-log plots of observed pressure change and/or pressure derivative plots versus recovery time are commonly used as the primary means for analyzing pressure fall-off tests. In addition to determining specific well performance conditions (e.g., well skin) and aquifer hydraulic property and boundary conditions, the presence of prevailing flow regimes can be identified (e.g., wellbore storage, linear, radial, spherical, double-porosity, etc.) based on characteristic diagnostic fall-off pressure derivative patterns. A more extensive list of diagnostic derivative plots for various formation and boundary conditions is presented by Horne (1990) and Renard et al. (2009).

As discussed by the EPA (2002), early pressure fall-off recovery response corresponds to flow conditions within and in proximity to the well bore, while later fall-off recovery response is reflective of progressively more distant reservoir conditions from the injection well location. Significant divergence in pressure fall-off response patterns from previous pressure fall-off tests (e.g., accelerated pressure fall-off recovery rates) may be indicative of a change in well and/or reservoir conditions (e.g., reservoir leakage). A more detailed discussion of using diagnostic plot analysis of pressure fall-off tests for discerning possible changes to well and reservoir conditions is presented by the EPA (2002, 2003).

As indicated by the EPA (2012), quantitative analysis of the pressure fall-off test data can be used to determine formation hydraulic property characteristics (e.g., permeability, transmissivity), and well skin factor (additional pressure change effects due to altering the permeability/storativity conditions of the reservoir/well injection interval boundary). Determination of well skin is a standard result for pressure fall-off test analysis and is described in standard well-test analysis texts such as that by Earlougher (1977). Software programs are also commercially available (e.g., Duffield 2007, 2009) for analyzing pressure fall-off tests. Significant changes in well and reservoir property characteristics (as determined from pressure fall-off analysis), compared to those used in site computational modeling and AoR delineation, may signify a reevaluation of the AoR, as may be required by the UIC Program Director, as noted by the EPA (2012).

B.6.5 Quality Control

Periodic QC checks will be routinely made in the field, and on occasion, where permanent pressure gauges are used, a second pressure gauge with current certified calibration will be lowered into the well to the same depth as the permanent downhole gauge.

B.6.6 Instrument/Equipment Testing, Inspection, and Maintenance

All field equipment will be visually inspected and tested prior to use. Spare instruments, batteries, etc. will be stored in the field support trailer.

B.6.7 Instrument/Equipment Calibration and Frequency

Pressure gauges that are used to conduct fall-off tests will be calibrated in accordance with manufacturers' recommendations, and current calibration certificates will be provided with test results to the EPA. In lieu of removing the injection tubing to regularly recalibrate the downhole pressure gauges, their accuracy will be demonstrated by comparison to a second pressure gauge, with current certified calibration, that will be lowered into the well to the same depth as the permanent downhole gauge. Calibration curves, based on annual calibration checks (using the second calibrated pressure gauge) developed for the downhole gauge, can be used for the purpose of the fall-off test. If used, these calibration curves (showing all historic pressure deviations) will accompany the fall-off test data submitted to the EPA.

B.7 Carbon Dioxide Plume and Pressure-Front Tracking

This section describes the experimental design, sampling methods, sample handling and custody, analytical methods, quality controls, and instrumentation/equipment specific to CO_2 plume and pressure-front tracking activities. Refer to Sections B.12 through B.14 for general descriptions of material inspection/acceptance methods, non-direct measurements (e.g., existing data), and data management.

B.7.1 Sampling Process Design (Experimental Design)

The Alliance will conduct direct and indirect CO_2 plume and pressure-front monitoring to meet the requirements of 40 CFR 146.90(g). The planned reservoir-monitoring well network design is based on the Alliance's current conceptual understanding of the site and predictive simulations of injected CO_2 fate and transport. The number, layout, design, and sampling regimen of the monitoring wells are based upon site-specific characterization data collected from the stratigraphic well, as well as structural dip, expected ambient flow conditions, and potential for heterogeneities or horizontal/vertical anisotropy within the injection zone and model predictions.

The planned monitoring well network for direct plume and pressure-front monitoring consists of two sets of monitoring wells: single-level in-reservoir (SLR) wells and reservoir access tube (RAT) wells (Figure

A.3). Two SLR wells will monitor the injection zone beyond the east and west ends of the horizontal CO_2-injection laterals. One of the SLR wells (SLR2; reconfigured stratigraphic well) will be located to the east-northeast of the injection well pad between the projected 10- to 20-year plume boundaries and the other well (SLR1) will be located to the west of the injection well pad within the projected 2-year plume boundary. An additional SLR well will be constructed within 5 years from the start of injection. The location will be informed by any observed asymmetry in pressure front development and will be located outside the CO2 plume extent. The distance from the plume boundary will be based on the monitoring objective of providing information that will be useful for both leakage detection and model calibration within the early years of operation. It is estimated that the well will be located less than 5 miles from the projected plume extent in order to provide an intermediate-field pressure monitoring capability that would benefit leak detection capabilities and meet the EPA requirement for pressure monitoring outside the CO_2 plume.

Three RAT wells will be installed within the boundaries of the projected 1- to 3-year CO_2 plume. The RAT well locations were selected to provide information about CO_2 arrival at different distances from the injection wells and at multiple lobes of the CO_2 plume. The RATs will be completed with nonperforated, cemented casings and will be used to monitor CO_2 arrival and quantify saturation levels via downhole PNC (geophysical logging across the reservoir and confining zone).

The reservoir-monitoring network will address transport uncertainties by using an "adaptive" or "observational" approach to monitoring (i.e., the monitoring approach will be adjusted as needed based on observed monitoring and updated modeling results). It is recognized that additional contingency wells may be required in out-years to monitor evolution of the CO_2 plume and fully account for the injected CO_2 mass.

Direct Pressure Monitoring

Continuous monitoring of P/T/SpC will be conducted in the SLR monitoring wells to track the pressure front and inform the monitoring and modeling programs.

Instruments will be installed at each SLR monitoring well to facilitate near-continuous monitoring of indicator parameters of CO_2 arrival and/or changes in brine composition. (Tables A.3 and A.8 list the parameters and instrumentation that will be used in the SLR wells.)

Fluid P/T/SpC are the most important parameters to be measured in real time within the monitoring interval of each well. These are the primary parameters that will indicate the presence of CO_2 or CO_2-induced brine migration into the monitored interval. In addition, pH and Eh (oxidation potential) measurements may be useful for detecting dissolved CO_2 and assessing water chemistry changes in the monitored interval. An initial evaluation of probes that are capable of measuring the desired parameters will assess the measurement accuracy, resolution, and stability for each parameter prior to selection and procurement of sensors for the full monitoring well network.

Pressure is expected to increase at the SLR monitoring wells installed within the injection reservoir soon after the start of injection and before the arrival of CO_2 because of the pressurization of the reservoir. Pressure will also be monitored to ensure that pressure within the injection interval does not exceed design specifications and to determine whether any observed pressure changes above the primary confining zone could be associated with a leakage response. Changes in other parameters are expected to occur later in time than the initial increase of pressure.

Direct Geochemical Plume Monitoring

Fluid samples will be collected from the SLR monitoring wells 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. Baseline monitoring will involve collection and analysis of a minimum of three rounds of aqueous samples from each well completed in the targeted injection zone prior to initiation of CO_2 injection. A comprehensive suite of geochemical and isotopic analyses will be performed on fluid samples collected from the reservoir. These analytical results will be used to characterize baseline geochemistry and provide a metric for comparison during operational phases. Aqueous sampling will not be used to assess CO_2 saturation levels. Once $scCO_2$ arrives, these wells can no longer provide representative fluid samples because of the two-phase fluid characteristics and buoyancy of $scCO_2$.

B.7.2 Sampling Methods

Direct Pressure Monitoring

A single probe incorporating electronic sensors that will monitor indicator parameters (P/T/SpC) will be placed at reservoir depth in each monitored well. Each parameter will be measured at a 10-minute sampling interval and will be transmitted to the surface via the wireline cable. Additional sensors may be installed at the wellhead for measuring parameters such as wellhead pressure, barometric pressure, and ambient surface temperature. A data-acquisition system will be located at the surface to store the data from all sensors at the well site and will periodically transmit the stored data to the MVA data center in the control building.

Direct Geochemical Plume Monitoring

Fluid samples will be collected at monitored formation depths and maintained at formation pressures within a closed pressurized sample container to prevent the escape of dissolved gases. Access to the monitored interval at the SLR wells will be through an inner 2-7/8-in. tubing string extending to the monitoring interval and packed-off just above the screen.

Fluid samples will be collected within the open interval of each monitoring well using a flow-through sampler with a 950-cc (or larger) sample chamber. The samples will be maintained at formation pressure within a closed sample container to prevent the escape of dissolved gases. Prior to sampling, the P/T/SpC probe will be monitored as the well is purged (up to three times the volume of the well-screen section will be discharged from the well before collecting the sample). The probe will then be removed from the well and the sampler will be run into the borehole on the same wireline cable to collect the pressurized fluid sample. Additional purging may be conducted just prior to collection of the pressurized fluid sample if mixing between the fluid column and sampling interval during insertion of the sampler is a concern.

B.7.3 Sample Handling and Custody

Direct Pressure Monitoring

P/T/SpC measurements will be recorded by a data logger at each well site and also transmitted to data-acquisition systems located in the MVA data center.

Electronic data and field records will be transferred to laptop and/or desktop computers and/or backed-up on secured servers at least quarterly, as well as scanned copies of all pertinent hardcopy field records/notes.

Direct Geochemical Plume Monitoring

After removing the aqueous sampler from the well, the closed and pressurized sample container(s) will be transported to the MVA laboratory space in the control building for processing using standard chain-of-custody procedures.

B.7.4 Analytical Methods

Table A.7 summarizes the analytical methods for groundwater quality monitoring in the SLR wells. Where possible, methods are based on standard protocols from the EPA or Standard Methods for the Examination of Water and Wastewater (American Public Health Association, American Water Works Association, Water Environment Federation, 19th ed. or later, Washington, D.C.). Laboratories shall be required to have standard operating procedures for the analytical methods performed.

B.7.5 Quality Control

Direct P/T/SpC and other continuous monitoring equipment will be calibrated according to manufacturers' recommendations. If trends or other unexplained variability in the data are observed that might indicate a suspect response, instruments will be evaluated and, if required, recalibrated, or replaced.

The QC practices for groundwater monitoring of the geochemical plume are the same as those specified for groundwater monitoring above the confining zone (Section B.4.5). Field QC samples include field blanks and field duplicates; a minimum of one of each type of sample shall be collected at each sampling event. Laboratory QC samples include method blanks, laboratory duplicates, matrix spikes, matrix spike duplicates, and laboratory control samples. The frequencies of these samples will be determined by the laboratory contract and standard method protocols. Typically, method blanks and laboratory control samples are analyzed with every analytical batch, while the remaining QC samples are run at a frequency of 1 per 10 samples. Table A.8 lists additional, method-specific requirements.

B.7.6 Instrument/Equipment Testing, Inspection, and Maintenance

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, the methods and standards used, and the date calibration will expire.
- 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 that they are functioning (reading/transmitting) correctly.

For groundwater sampling, field equipment will be maintained, factory serviced, and factory calibrated according to the manufacturers' recommendations. Spare parts that may be needed during sampling will be included in supplies on-hand during field sampling.

For all laboratory equipment, testing, inspection, and maintenance will be the responsibility of the analytical laboratory per method-specific protocols and the laboratory's QA program. The laboratory's QA program will be reviewed by the Alliance prior to submission of samples for analysis.

B.7.7 Instrument/Equipment Calibration and Frequency

Pressure gauges that are used for direct pressure monitoring will be calibrated according to manufacturers' recommendations, and current calibration certificates will be kept on file with the monitoring data.

B.8 Pulsed-Neutron Capture Logging

PNC wireline logs will be used to quantify CO_2 saturation relative to depth in each of three monitoring RAT wells. These indirect measurements of CO_2 saturation will be used to detect and quantify CO_2 levels over the entire logged interval. The PNC logging data will be used for calibration of reservoir models and to identify any unforeseen occurrences of CO_2 leakage across the primary confining zone. Numerical modeling will be used to predict the CO_2 plume growth and migration over time by integrating the calculated CO_2 saturations in the three RAT wells with the geologic model and other monitoring data.

B.8.1 Sampling Process Design (Experimental Design)

PNC logs operate by generating a pulse of high-energy neutrons and subsequently measuring the neutron decay over time and across a wide energy spectrum. PNC logs can measure specific energy bins or a composite of energies, the latter of which is termed the thermal capture cross-section (sigma) operational mode. In sigma mode, all elements that capture and slow neutrons contribute to the measurement rather than just the characteristic energy levels associated with specific elements. Both measurement modes are useful for determining CO_2 saturation from PNC logs and will be simultaneously acquired.

PNC logging has been successfully implemented at a number carbon sequestration sites and while the PNC method has been shown to work quite well, problems associated with CO_2 flooding the casing and perforation zones have been identified. PNC logs are only sensitive to a localized region surrounding the borehole (15−30 cm) and are therefore susceptible to interference from features very near the borehole, such as changing borehole fluids, poor cement, or invaded drilling fluids. The monitoring RAT wells are designed with small-diameter, nonperforated casings to minimize near-borehole interference effects. Borehole effects will also be accounted for by analyzing response times from multiple detectors in the tool. Porosities within the reservoir at the FutureGen 2.0 storage site are moderate and the PNC logs are expected to adequately quantify CO_2 saturation along the RAT boreholes in order to calibrate reservoir models as well as identify possible leakage through the sealing layers.

B.8.2 Sampling Methods

Quarterly PNC logging will be conducted in RAT wells 1, 2, and 3. The locations of the RAT wells was chosen to sample various stages of the CO_2 plume migration, with the emphasis on the areas with large expected changes in the first five (5) years. Downhole repeatability of the tool performance will be verified by conducting a "repeat section" of the logging run. Repeatability is used to validate the measurement acquired during the main logging pass, as well as to identify anomalies that may arise during the survey for re-logging. Measurement depth is of critical importance in all borehole logs. Depth will be measured with respect to a fixed reference throughout the lifetime of the project. Verification of proper tool operation will be performed prior to each logging event following the manufacturer's recommended procedure. Elastic cable stretch and slippage will be automatically compensated. Repeatability of logging depths will also be checked by repeat gamma-ray depth location of key strata or drill collar locators and can be used to correct depth measurements after logging is complete.

B.8.3 Sample Handling and Custody

No specialized sample-/data-handling procedures are required. PNC tool readings will be recorded on a computer located in the wireline logging truck. All electronic data and field records will be transferred to laptop and/or desktop computers and backed-up, on secure servers at the conclusion of each logging event, as will scanned copies of all pertinent hardcopy field records/notes.

B.8.4 Analytical Methods

PNC log data will be processed following industry best practices and coordinated with the borehole-logging operator to optimize data-collection parameters. Modeling can be done to simulate near-borehole interferences and remove their effects from the signal. Modeling is a recommended procedure and requires knowledge of the target formations and fluids that must be obtained from cores and additional logging data. Each logging result will be compared for each RAT well to the baseline or previous survey, as applicable, to determine changes in saturation.

B.8.5 Quality Control

Verification of vendor processing software and results will ensure that the acquired data are acceptable and that calculations of CO_2 saturations are reproducible. Third-party PNC logging and processing for a subset of boreholes and logging events can be used as part of the validation procedure. Failure of tool performance in the field or unreproducible "repeat sections" will result in non-acceptance of the data and may trigger a return of the PNC tool to the manufacturer for recalibration or replacement. Off-normal CO_2 saturation calculations will trigger additional evaluation and possible new logging runs.

B.8.6 Instrument/Equipment Testing, Inspection, and Maintenance

Examples of industry-published guidelines for calibration and field operation of the PNC wireline log hardware and data-collection software are provided in Appendix B.

B.8.7 Instrument/Equipment Calibration and Frequency

To ensure data-acquisition quality, the logging tool will be calibrated for accuracy, checked to be in good working order, and verified by the manufacturer. All tools and field operation software will be provided by the manufacturer with an auditable verification record to ensure traceability. In addition to the initial manufacturer calibration, PNC tool recalibration will be performed monthly and both prior to and after each logging event using an onsite calibration vessel following the manufacturer's guidelines. Examples of industry-published guidelines for calibration and field operation of the PNC wireline log hardware and data-collection software are provided in Appendix B.

B.9 Integrated Deformation Monitoring

B.9.1 Sampling Process Design (Experimental Design)

The deformation monitoring will include orbital DInSAR data (X-band TerraSAR-X, C-band Radarsat-2, X-Band Cosmo-Skymed, or any other satellite data that will be available at the time of data collection) and a field survey validation using permanent Global Positioning System (GPS) stations, permanent tiltmeters, and annual Differential Global Positioning System (DGPS) surveys. This approach will be used for the baseline before the injection and during the injection phase with modifications based on the experience gained during the two-year baseline-monitoring period.

Differential Synthetic Aperture Radar (SAR) Interferometry (DInSAR) is a method of generating surface displacement maps from two images acquired by radar aboard a satellite at distinct times. Specific and complex processing is applied to obtain time series of displacements of the ground surface. All DInSAR deformation measurements are corrupted by spatiotemporal variations in the atmosphere and surface scattering properties. Advanced DInSAR time-series analyses exploit a subset of pixels in a stack of many SAR images to reduce atmospheric artifacts and decorrelation effects. These pixels exhibit high phase stability through time. The output products from these advanced techniques include a pixel average velocity accurate to 1–2 mm/yr and a pixel time series showing cumulative deformation accurate to 5–10 mm for each of the SAR acquisition times. It should be noted that accuracy improves with time as the time series becomes larger.

B.9.2 Sampling Methods

Orbital SAR data will be systematically acquired and processed over the storage site with at least one scene per month to obtain an advanced DInSAR time series. These data will be obtained from the available orbital instruments available at the time of collection. It should be noted that the existing TerraSAR-X, Radarsat-2 and Cosmo-Skymed systems provide frequent systematic revisits of 11, 24, and 4 days, respectively.

Widespread overall temporal decorrelation is anticipated except in developed areas (e.g., roads, infrastructure at the site, and the neighboring towns) and for the six corner cube reflectors that will be deployed on site. These isolated coherent pixels will be exploited to measure deformation over time, and different algorithms (e.g., persistent scatters, small baseline subsets, etc.) will be used to determine the best approach for the site.

Data from five permanent tiltmeters and GPS stations will be collected continuously. In addition, annual geodetic surveys will be conducted using the Real-Time Kinematic (RTK) technique where a single reference station gives the real-time corrections, providing centimeter-level or better accuracy. Deformations will be measured at permanent locations chosen to measure the extent of the predicted deformation in the AoR and also used by the gravity surveys (see Section B.10).

B.9.3 Sample Handling and Custody

DInSAR data will be acquired, processed, and archived by the vendor. Displacement maps and deformation time series will be archived on digital media by the Alliance.

Permanent GPS and tiltmeter data will be collected in real time by the Alliance and stored on digital media on site. Differential GPS (DGPS) survey data will be archived on digital media by the Alliance.

B.9.4 Analytical Methods

To establish a more comprehensive geophysical and geomechanical understanding of the FutureGen 2.0 site, DInSAR and field deformation measurements will be integrated and processed with other monitoring data collected at the site: microseismicity, gravity, pressure, and temperature. This unique and complete geophysical data set will then be inverted to constrain the CO_2 plume shape, extension, and migration in the subsurface.

B.9.5 Quality Control

Verification of vendor processing software and results will ensure that the acquired data are acceptable and results reproducible.

B.9.6 Instrument/Equipment Testing, Inspection, and Maintenance

Testing of the whole DInSAR chain acquisition is routinely conducted by the space agencies.

Permanent tiltmeters and GPS instruments installed onsite will be checked annually.

The Trimble R8 receivers used for the annual DGPS surveys will be checked annually.

B.9.7 Instrument/Equipment Calibration and Frequency

Calibration of DInSAR chain acquisition is routinely conducted by the space agencies and the results will be compared to field measurements.

Tiltmeters and GPS instruments installed onsite will be calibrated for accuracy, checked to be in good working order, and verified by the manufacturer. The Trimble R8 receivers used for the annual DGPS surveys will also be calibrated and verified by the manufacturer.

All equipment and software will be provided by the manufacturer with an auditable verification record to ensure traceability.

B.10 Time-Lapse Gravity Monitoring

B.10.1 Sampling Process Design (Experimental Design)

Four-dimensional (4D or time-lapse) microgravimetry—the temporal change of gravity at the microGal scale (1 $\mu Gal = 10^{-6}$ m/s^2)—is a cost-effective and relatively rapid means of observing changes in density distribution in the subsurface, particularly those caused by the migration of fluids.

Time-lapse gravity monitoring is accomplished using repetitive annual surveys at a series of points located at the ground surface (permanent stations). Changes in gravity anomaly with time are determined and then interpreted in terms of changes in subsurface densities. These changes could be linked for example to replacement of water by CO_2. providing an indirect method of tracing the displacement of the CO_2 plume at depth. Due to the non-uniqueness of the solution, this monitoring method could rarely be used alone and gives the best results when used with other methods (deformation or seismic).

B.10.2 Sampling Methods

Permanent station locations were established in November 2011 for the purpose of future reoccupation surveys (Figure A.4). These stations are located on the roadways inside the survey area, the reference being the KC0540 station (Central Plaza Park monument, Jacksonville, Illinois). The emplacement of each permanent station on the roadway is designated by a marker. Markers are approximately half-inch-diameter nails with a three-quarter-inch heads to provide good visibility from the surface.

Because all the gravity measurements are relative, a tie to a gravity station outside the surveyed area must be made. This reference is station NGS# KC0540, a monument located in Central Plaza Park in Jacksonville, Illinois, which was tied to the absolute gravity station NGS# KC0319 located in Hannibal, Missouri.

To compensate for the instrumental drift, measurements are taken on a 2-hour cycle at a local reference station at the center of the surveyed area (station 137) and at an offsite location (station KC0540) twice a day.

B.10.3 Sample Handling and Custody

Data will be archived on a digital media by the Alliance.

B.10.4 Analytical Methods

Data reduction will be performed using the standardized methods to obtain Free Air and Bouguer anomalies. These anomalies will then be interpreted in terms of subsurface density anomalies by gravity direct or inverse modeling using the commercial software ENcom Model Vision™ 12.0.

B.10.5 Quality Control

Repeat measurements at the same field point is the only way to evaluate their quality. At least three measurements for each point will be recorded.

B.10.6 Instrument/Equipment Testing, Inspection, and Maintenance

The gravity meter used will be a LaCoste & Romberg Model D belonging to Pacific Northwest National Laboratory. It is a steel mechanism, "zero length" spring meter with a worldwide range that is less prone to drift than quartz meters. The instrument is thermostatically controlled to approximately 50°C during the duration of the surveys. A full maintenance and inspection of the instrument needs to be completed every 10 years at the LaCoste and Romberg factory; the next one is scheduled in 2021.

B.10.7 Instrument/Equipment Calibration and Frequency

No calibration of the instrument is required.

B.11 Microseismic Monitoring

Elevated pressures in the reservoir due to injection of CO_2 have the potential to induce seismic events. The objective of the microseismic monitoring network is to accurately determine the locations, magnitudes, and focal mechanisms of seismic events.

B.11.1 Sampling Process Design (Experimental Design)

A microseismic monitoring system must be able to detect a seismic event at a number of monitoring stations and use the signals to accurately determine the event location and understand the brittle failure mechanisms responsible for the event. The monitoring network consists of an array of seismic sensors placed either at the near-surface or within deeper monitoring boreholes. The accuracy of the network is dependent on both the geometry of the sensor array and the signal-to-noise ratio (SNR) at each of the sensor locations. The number and spatial distribution of sensors in a microseismic monitoring network must be designed to minimize the errors in estimating event location and origin times. The subsurface seismic velocity model also has a large influence on the predicted data and must be estimated as accurately as possible using borehole logs and data from vertical seismic profiling. Sensors need to have high sensitivity, flat response over the intended frequency range, a low noise floor, and stable performance over time.

External noise sources often occur at the surface or from nearby subsurface activities such as drilling. Surface noise attenuates with distance below the surface and it is therefore advantageous to emplace surface sensors within shallow boreholes in order to reduce external noise to an acceptable level. Surface or shallow borehole sensors provide multiple sensing azimuths and offsets, but surface sensors typically suffer from lower SNRs. Shallow borehole installations, however, can achieve a noise floor approaching that of sensors located in deep boreholes. Deep borehole monitoring can provide a higher SNR if the microseismic event occurs close enough to the array, but precise event location can be difficult due to geometric constraints on the array.

B.11.2 Sampling Methods

The microseismic network will consist of an array of near-surface shallow borehole sensors in addition two deep borehole sensor arrays installed within the ACZ wells. The network incorporates the benefits of both array types to improve the overall performance of the system and is expected to perform well for monitoring seismic events that occur in the AoR.

Commonly used sensors for seismic applications include moving coil geophones that that have frequency bandwidths from 5−400 Hz. These devices are often built with signal conditioning and digitizer circuitry located on the sensor to improve the electrical performance; however, because of the complexity of their assembly, their long-term deployment in a deep borehole environment results in reduced lifetimes. Permanent emplacement of standard moving coil geophones within a deep borehole would not be expected to last the lifetime of the FutureGen 2.0 project. Geophones will be placed in the shallow borehole stations and are expected to perform well in that environment, particularly for higher-frequency signals.

Surface sensors also require higher sensitivities and lower noise floors than sensors placed in deep boreholes because the distance from the event to the surface is often much greater. High-quality broadband seismometers exhibit much higher sensitivity and extremely low noise floors compared to standard geophones. These seismometers have long working lifetimes and an excellent frequency response from 1 mHz to 200Hz. Seismometers will also be installed in each shallow borehole along with a borehole geophone. To minimize signal attenuation and site noise, the boreholes will be drilled to at least the uppermost bedrock unit, and the casing will be sealed and pumped dry prior to sensor emplacement.

Fiber-optic-based seismic sensors use backscattered light from a laser pulse that has been introduced into an optical fiber to measure the movement of a sensing element. The fiber can be coupled to a device to mechanically amplify the strain on the fiber and produce a sensor with performance as good as, or better than, standard geophones. A key feature of these sensors is that because they have no electronics located within a borehole they are extremely robust; their lifetimes and performance stability are designed to last several decades. Due to their superior sensitivity and expected longevity, an array of fiber-optic accelerometers will be installed within two, deep ACZ wells. Optical cables will be extended from each of the wells back to a central control building that will house the data-acquisition and storage systems.

B.11.3 Sample Handling and Custody

No specialized sample/data handling procedures are required. Microseismic signals from the shallow boreholes will be continuously recorded on a data logger located at each of the stations. All electronic data will be continuously transferred to a data storage and processing system located at a central control building. Digital copies of all pertinent hardcopy field records/notes will also be transferred to the central data server.

B.11.4 Analytical Methods

Microseismic data will be processed and stored following industry best practices.

B.11.5 Quality Control

Verification of vendor processing software and results will ensure that the acquired data are acceptable and that determinations of event locations and focal mechanisms are accurate.

B.11.6 Instrument/Equipment Testing, Inspection, and Maintenance

Regular maintenance and testing of the seismic hardware and data-collection software are critical to ensuring high-quality results. All hardware will be maintained in accordance with manufacturer recommendations. Software updates will be incorporated as they are released by the manufacturer.

B.11.7 Instrument/Equipment Calibration and Frequency

All microseismic equipment will be calibrated for accuracy, checked to be in good working order, and verified by the manufacturer. All equipment and software will be provided by the manufacturer with an auditable verification record to ensure traceability. In addition to the initial manufacturer calibration, seismometers and geophones will be periodically recalibrated following the manufacturers' guidelines. In the event that damage is identified, it will be immediately reported and the equipment removed and replaced.

B.12 Inspection/Acceptance of Supplies and Consumables

Testing and monitoring supplies and consumables that may affect the quality of the results will be procured, inspected, and accepted in accordance with the Alliance representative's administrative procedures (e.g., Pacific Northwest National Laboratory's HDI Workflows and Work Controls).

Critical items and responsible personnel will be identified in task-specific sampling and analysis plans, as appropriate.

B.13 Non-direct Measurements (e.g., existing data)

Existing data, including literature files and historic data from surrounding areas and previous onsite characterization, testing, and monitoring activities, have been used to guide the design of the testing and monitoring program. However, these data are only ancillary to the well testing and monitoring program described here. These existing data will be used primarily for qualitative comparison to newly collected data.

All data will continue to be evaluated for their acceptability to meet project needs, that is, that the results, interpretation, and reports provide reasonable assurance that the project is operating as permitted and is not endangering any USDWs.

B.14 Data Management

All project data, record keeping, and reporting will be conducted to meet the requirements of 40 CFR 146.91(f).

B.14.1 Data Management Process

Project data will be managed in accordance with the Project Data Management Plan (Bryce et al. 2013). Management of all monitoring data is controlled by the subtier Monitoring Data Management Plan (Vermeul et al. 2014; not publicly available). Management of well MIT data is controlled by the subtier Well Construction Data Management Plan (Lanigan et al. 2013; not publicly available). All data will be managed by Alliance representatives throughout the duration of the project plus at least 10 years.

B.14.2 Recordkeeping Procedures

Project records will be managed according to project record management requirements and Alliance representatives' internal records management procedures.

B.14.3 Data Handling Equipment and Procedures

All data will be managed in a centralized electronic data management system. The underlying electronic servers will be routinely maintained, updated, and backed-up to ensure the long-term preservation of the data and records.

The centralized data-management system acts as a "data hub" to support collaborative analyses, enabling a diverse spectrum of experts—including geologists, hydrologists, numerical modelers, model developers, and others—to share data, tools, expertise, and computational models. This data-management system also acts as a "turn-key" data-management system that can be transferred to any future Alliance representatives or storage site operators.

B.14.4 Configuration Management and Change Control

The project's Configuration Management Plan (Alliance 2013b) identifies configuration-management requirements and establishes the methodology for configuration identification and control of releases and changes to configuration items. Each Alliance contractor is required to use configuration management to establish document control and to implement, account for, and record changes to various components of the project under its responsibility. The project's data configuration process is detailed in the Project Data Management Plan (Bryce et al. 2013) and its subsequent subtier data management plans. This data configuration process controls how changes are made should errors or loss of data be detected during the course of routine data quality and readiness review checks and/or peer reviews.

QC mechanisms, checklists, forms, etc. used to detect errors are highly data-specific, but generally rely on spot-checks against field and laboratory records, as well as manual calculations to validate electronic manipulation of the data.

C. Assessment and Oversight

C.1 Assessments and Response Actions

As described in Section A.6 and detailed in Table A.2, the Monitoring, Verification, and Accounting (MVA) program for the FutureGen 2.0 CO_2 Pipeline and Storage Project includes numerous categories, methods, and frequencies of monitoring the performance of the CO_2 storage site. FutureGen staff responsible for the associated technical element or discipline will analyze the monitoring data and initiate any needed responses or corrective actions. Management will have ready access to performance data and will receive monitoring and performance reports on a regular basis.

In addition to the activities covered by the MVA program, data quality assessments will be performed to evaluate the state of configuration-controlled technical information in the FutureGen technical data repository to ensure that the appropriate data, analyses, and supporting information are collected, maintained, and protected from damage, deterioration, harm, or loss. These data quality assessments will be performed by a team consisting of the FutureGen 2.0 Data Manager, Project Quality Engineer, Subject Matter Experts, and additional knowledgeable and trained staff as appropriate for the scope and nature of the assessment. Assessments will be scheduled to occur at logical points in the project lifecycle, such as after completion and submission of a major deliverable that incorporates controlled technical information. Assessment results will be reported to management; deficiencies, weaknesses, opportunities for improvement, and noteworthy practices will be identified in the assessment reports. Assessment results will also be communicated to affected parties. Management will assign responsible staff to correct deficiencies and other nonconforming conditions and will ensure that corrective actions are implemented and verified in a timely manner. The Project Quality Engineer and FutureGen Data Manager will conduct follow-up surveillances to verify and document completion of corrective actions and to evaluate effectiveness.

C.2 Reports to Management

Management will be informed of the project status via the regular monitoring and performance reports generated by the MVA program, as well as reports of assessments conducted to verify data quality and surveillances performed to verify completed corrective actions. These reports are described in Section C.1; additional periodic reporting is not anticipated at this time. However, as directed by FutureGen management, targeted assessments by the Data Manager, Project Quality Engineer, or others will be conducted and reported to apprise management of project performance in areas of particular interest or concern.

D. Data Validation and Usability

D.1 Data Review, Verification, and Validation

The FutureGen 2.0 CO_2 Pipeline and Storage Support Project has established a Project Data Management Plan (PDMP) (Bryce et al. 2013) to identify how information and data collected or generated for the project will be stored, organized, and accessed to support all phases of the project. The PDMP describes the institutional responsibilities and requirements for managing all relevant data, including the intended uses and level of quality assurance needed for the data, the types of data to be acquired, and how the data will be managed and made available to prospective users. In addition to the PDMP, the FutureGen 2.0 project has issued discipline-specific subtier Technical Data Management Plans (TDMPs) to tailor data management processes to the needs of specific technical elements (e.g., computational modeling, geophysical, monitoring, site characterization). The PDMP and each TDMP define several categories of data, or Data Levels (consistent among all of the Data Management Plans), with corresponding data management, review, verification, validation, and configuration control requirements. The PDMP and TDMPs establish roles (e.g., Data Manager, Data Steward, Data Reviewer, Subject Matter Expert) and responsibilities for key participants in the data management process; project management assigns appropriate staff members to each role. Project staff who generate, review, verify, validate, or manage data are trained to the requirements of one or more Data Management Plans. Raw data (resulting from the use of a procedure or technology), defined as Level 1, are put under configuration control in the data management system at the time of upload to the system. Data defined at other Data Levels are put under configuration control when the data become reportable or decision-affecting. The procedures used to verify, validate, process, transform, interpret, and report data at each Data Level are documented and captured as part of the data management process.

D.2 Verification and Validation Methods

The Data Management Plans described in Section D.1 require that data packages undergo rigorous peer reviews. These reviews both *validate* the data—confirm that the appropriate types of data were collected using appropriate instruments and methods—and *verify* that the collected data are reasonable, were processed and analyzed correctly, and are free of errors. Data that have not undergone the peer-review process and are not yet under configuration control can be provided as preliminary information when accompanied by a disclaimer that clearly states that data are 1) preliminary and have not been reviewed in accordance with FutureGen's quality assurance practices, 2) considered "For Information Only", and 3) not to be used for reporting purposes nor as the basis for project management decisions. Once data are placed under configuration control, any changes must be approved using robust configuration-management processes described in the Data Management Plans. The peer-review and configuration-management processes include methods for tracking chain-of-custody for data, ensuring that custody is managed and control is maintained throughout the life of the project.

If issues are identified during a peer review, they are addressed and corrected by the data owner and peer reviewer (involving others, as necessary) as part of the peer-review process. These unreviewed data will not have been used in any formal work product nor as the basis for project management decisions, so the impacts of data errors will be minimal. If an error is identified in data under configuration control, in addition to correcting the error, affected work products and management decisions will be identified, affected users will be notified, and corrective actions will be coordinated to ensure that the extent of the error's impact is fully addressed.

D.3 Reconciliation with User Requirements

During the course of a long-duration project such as the FutureGen 2.0 CO_2 Pipeline and Storage Project, personnel changes over time can result in loss of institutional memory about the organization's data, thereby reducing the value of the data. New project staff may have little understanding of the content, intended uses, and pedigree of existing data sets. Metadata can help protect the organization's investment in data by providing context and pedigree, as well as describing interrelationships between various data sets. The Data Management Plans described in Section D.1 provide for Subject Matter Experts (SMEs) to establish and document metadata requirements for the data sets created by the FutureGen 2.0 project. Complete metadata will support data interpretation, provide confidence in the data, and encourage appropriate use of the data. To establish meaningful metadata requirements, SMEs must understand how data users and decision-makers will use the data. By adhering to metadata requirements when loading data into the project data repository, project staff ensure that user requirements addressed by the metadata are satisfied.

Data reviews, identification and resolution of data issues, and limitations on data use are discussed in Section D.2.

E. References

40 CFR 146. Code of Federal Regulation, Title 40, Protection of Environment, Part 146, Underground Injection Control Program: Criteria and Standards.

Alliance (FutureGen Industrial Alliance, Inc.). 2013a. *CO_2 Pipeline and Storage Project Phase II, Project Management Plan*. FGA-02-PMP – Revision 1. Washington, D.C.

Alliance (FutureGen Industrial Alliance, Inc.). 2013b. *Configuration Management Plan*. Phase II, FG-02-CMP, Rev. 0, Washington, D.C.

American Public Health Association, American Water Works Association, Water Environment Federation, 19th ed. or later, Washington, D.C.

American Society for Testing and Materials (ASTM). 2011. *Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens*. ASTM G1-03(2011), American Society for Testing and Materials, Philadelphia, Pennsylvania.

Bourdet, D., Ayoub, J.A. and Y.M. Pirard. 1989. "Use of pressure derivative in well-test interpretation." *SPE Formation Evaluation*, June 1989, pp. 293-302.

Bryce RW, GV Last, D C Lanigan, and TB Miley. 2013. *FutureGen 2.0 – CO_2 Pipeline and Storage Project, Project Data Management Plan.* Revision 2a, FG-02-PLN-PDMP, Rev 2a. Battelle Pacific Northwest Division, Richland, Washington.

Duffield, GM. 2007. *AQTESOLV for Windows Version 4.5 User's Guide*. HydroSOLVE, Inc., Reston, Virginia (http://www.aqtesolv.com).

Duffield GM. 2009. "Upgrading Aquifer Test Analysis, by William C. Walton." *Ground Water - Comment Discussion Paper*, 47(6):756-757.

Earlougher RC. 1977. *Advances in well test analysis*. Monograph Vol. 5, Society of Petroleum Engineers, Richardson, Texas.

EPA (United States Environmental Protection Agency). 2002. "UIC Pressure Falloff Testing Guideline." EPA Region 6, August 8 2002, Third Revision; available on the Internet at: http://www.epa.gov/region6/water/ swp/uic/guideline.pdf.

EPA (United States Environmental Protection Agency). 2003. "The Nuts and Bolts of Falloff Testing." EPA Region 6, March 5, 2003; available on the Internet at: http://www.epa.gov/safewater/dwa/pdfs/ 2%20uic%20modules/dwaUIC-2003falloffseminar.pdf.

EPA (United States Environmental Protection Agency). 2008. Determination of the Mechanical Integrity of Injection Wells. United States Environmental Protection Agency, Region 5 – Underground Injection Control (UIC) Branch Regional Guidance #5, Revised February, 2008. Online at http://www.epa.gov/r5water/uic/r5guid/r5_05_2008.htm

EPA (United States Environmental Protection Agency). 2012. "Geologic Sequestration of Carbon Dioxide: Draft Underground Injection Control (UIC) Program Class VI Well Testing and Monitoring

Guidance." January 2012; available on the Internet at: http://water.epa.gov/type/groundwater/uic/class6/upload/epa816r13001.pdf.

EPA (U.S. Environmental Protection Agency). 2013. *Geologic Sequestration of Carbon Dioxide: Underground Injection Control (UIC) Program Class VI Well Testing and Monitoring Guidance*. EPA 816-R-13-001, Washington D.C.

Horne RN. 1990. Modern well test analysis: a computer-aided approach. Petroway, Inc., Palo Alto, California.

Lanigan DC, GV Last, and TB Miley. 2013. *FutureGen 2.0 – CO2 Pipeline and Storage Project, Well Construction Data Management Plan*. Revision 0a, FG-02-PLN-TDMP02, Rev 0a, Battelle Pacific Northwest Division, Richland, Washington.

Muller N, TS Ramakrishnan, A Boyd, and S Sakruai. 2007. Time-lapse carbon dioxide monitoring with pulsed neutron logging. *International Journal of Greenhouse Gas Control* 1(4):456-472.

Renard P, D Glenz, and M Mejias. 2009. "Understanding diagnostic plots for well-test interpretation." *Hydrogeology Journal* 17(3):589-600.

Spane FA. 1993. *Selected Hydraulic Test Analysis Techniques for Constant-Rate Discharge Tests.* PNL-8539, Pacific Northwest Laboratory, Richland, Washington.

Spane FA and SK Wurstner. 1993. "DERIV: A program for calculating pressure derivatives for use in hydraulic test analysis." *Ground Water* 31(5):814:822.

Vermeul VR, RW Bryce, GV Last, DC Lanigan, and TB Miley. 2014. *FutureGen 2.0 – CO_2 Pipeline and Storage Project, Monitoring Data Management Plan*. FG-02-PLN-TDMP04, Rev 0, Battelle Pacific Northwest Division, Richland, Washington. (Not publicly available)