# Testing and Monitoring Plan

## About this Document

This document compiles text from the FutureGen permit application for Morgan County Class VI UIC Wells 1, 2, 3, and 4 into the testing and monitoring plan template provided in the *Class VI Project Plan Development Guidance*. The intent is to identify whether sufficient information was provided in the permit application to complete the project plans; **this is not considered a complete or approvable project plan**.

Identified deficiencies and questions are presented in highlighted text.

To facilitate reference to applicant submittals, text is color-coded and sections of the original documents are noted (some text has been edited slightly):

- Red text is from the FutureGen permit application.
- Blue text is from the additional information provided in November 2013.
- Green text is from the additional information provided in December 2013.
- Purple text is from the additional information provided in January 2014 (including the Testing and Monitoring spreadsheet).
- Highlighted text identifies EPA's comments provided in February 2014
  Text written by EPA is black.
- Text written by the Alliance is orange.

Table and figure numbers reflect the labels in FutureGen's submissions.

## Facility Information

*[from Section 1, Table 1.1]*

Facility information is provided by FutureGen in Section 1 of the FutureGen 2.0 permit application for Morgan County Class VI Underground Injection Control (UIC) Wells 1, 2, 3, and 4. The contact person at the FutureGen Morgan County Office was provided in the requests for additional information.

Facility name: FutureGen 2.0 Project: Morgan County Class VI UIC Wells 1, 2, 3, and 4

Facility contacts (names, titles, phone numbers, email addresses): Kenneth ~~Humphries~~Humphreys, Chief Executive Officer, FutureGen Industrial Alliance, Inc., Morgan County Office, 73 Central Park Plaza East, Jacksonville, IL 62650, 217-243-8215

Location (town/county/etc.): Morgan County, IL; 26−16N−9W; 39.800266ºN and 90.07469ºW”

## Approach and Strategy of the Monitoring Network

The selected monitoring network layout (Figure 1) and well design is based upon site-specific characterization data collected from the stratigraphic well at the Morgan County carbon dioxide ($CO_2$) storage site and from regional data. Placement of the wells has also been guided by the numerical modeling of the site along with practical considerations, driven primarily by land owner acceptance. The monitoring network will be in place and completely functional prior to any $CO_2$ injection and associated pressure buildup in order to establish the baseline conditions from which to compare and evaluate future injection/post-injection conditions.

The monitoring network is a comprehensive network designed to detect unforeseen $CO_2$ and brine leakage out of the injection zone and for the protection of the underground sources of drinking water (USDWs). Central to this monitoring strategy is the measurement of $CO_2$ saturation within the reservoir using three reservoir access tubes (RATs) extending to the base of the Mount Simon Formation. The $CO_2$ saturation will be measured using pulsed-neutron capture (PNC) logging across the injection zone and primary confining zone. PNC logging is a proven method for quantifying $CO_2$ saturation around the borehole. The three wells have been placed at increasing distances from the injection site to provide measures of $CO_2$ saturation at locations representing the predicted 2-, 3- and 4-year arrival times, respectively. The three RAT installations have also been distributed across three different azimuthal directions, providing $CO_2$ arrival information for three of the four predicted lobes of the $CO_2$ plume. These near-field $CO_2$ saturation measurements will allow for calibration of the numerical model early in the injection phase of the project and verify whether the $CO_2$ plume is developing as predicted. These wells will continue to be monitored for the development of $CO_2$ saturation across Mount Simon Formation for the duration of the project.

The monitoring network will also include two single-level reservoir (SLR) wells, completed across the planned injection interval within the Mount Simon Formation to continuously and directly measure for pressure, temperature, and specific conductance (P/T/SpC) over the injection and post-injection monitoring periods. Pressure at these locations will be compared with numerical model predictions and used to calibrate the model as necessary. These wells will initially be sampled for aqueous chemistry. However, once supercritical $CO_2$ ($scCO_2$) breakthrough occurs, these wells can no longer provide representative fluid samples because of the two-phase fluid characteristics and buoyancy of $scCO_2$.

Another central component of the monitoring strategy is to monitor for any unforeseen leakage from the reservoir as early as possible. This will be accomplished by monitoring for $CO_2$ and brine intrusion immediately above the confining zone. These two “early-detection” wells will be completed in the first permeable unit above the Eau Claire caprock, within the Ironton Sandstone. These wells will be continuously monitored for P/T/SpC, and periodically sampled to characterize aqueous chemistry. Leakage to the Above Confining Zone (ACZ)would most likely be identified based on pressure response, but it may also result in changes in aqueous chemistry. One of the ACZ wells will be located approximately 1,000 ft west of the injection well site, within the region of highest pressure buildup. The other ACZ well will be located approximately 0.75 mi west of the injection site within 50 ft of SLR1 and 500 ft of RAT1. Both of these ACZ well locations represent an area of increased potential for leakage (i.e., areas of increased pressure where wells penetrate the primary confining zone). If there are indications of leakage in these wells a modeling evaluation of any observed $CO_2$ migration above the confining zone will be used to assess the magnitude of $CO_2$ leakage and make bounding predictions regarding the expected impacts on shallower intervals, and ultimately, the potential for adverse impacts on USDW aquifers or other ecological impacts.

The monitoring network will also include one well located in the lowest USDW, the St Peter Sandstone. This well will be instrumented to monitor continuously for P/T/SpC, and periodically samples will be collected for characterizing aqueous chemistry.  This USDW well is co-located with the ACZ well located closest to the injection well site.

Comparison of observed and simulated arrival responses at the early-detection wells and shallower monitoring locations will be continued throughout the life of the project and will be used to calibrate and verify the model, and improve its predictive capability for assessing the long-term environmental impacts of any $CO_2$ leakage.  If deep early-detection monitoring locations indicate that primary confining zone leakage has occurred, a comprehensive near-surface-monitoring program could be activated to fully assess environmental impacts relative to baseline conditions.

Beyond the direct measures of the monitoring well network, two indirect monitoring techniques—deformation monitoring and microseismic monitoring—will be used to detect the development of the pressure front, which results from the injection of $CO_2$.  The objective of the deformation monitoring is to provide a means to detect the development of an asymmetric plume that would be different from the predicted plume shape.   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 monitoring network will address transport uncertainties by adopting an "adaptive" or "observational" monitoring approach (i.e., the monitoring approach will be adjusted as needed based on observed monitoring and updated modeling results).  This monitoring approach will continually evaluate monitoring results and make adjustments to the monitoring program as needed, including the option to install additional wells in outyears to verify $CO_2$ plume and pressure front evolution and/or evaluate leakage potential.  All wells will continue to be monitored for the duration of the project to characterize subsurface pressure and $CO_2$ migration and guide operational and regulatory decision-making.  To meet permit requirements for pressure front monitoring, at least one additional injection zone monitoring well will be installed outside the lateral extent of the $CO_2$ plume but within the lateral extent of the defined pressure front AoR.  This well will be installed within 5 years of the start of injection.

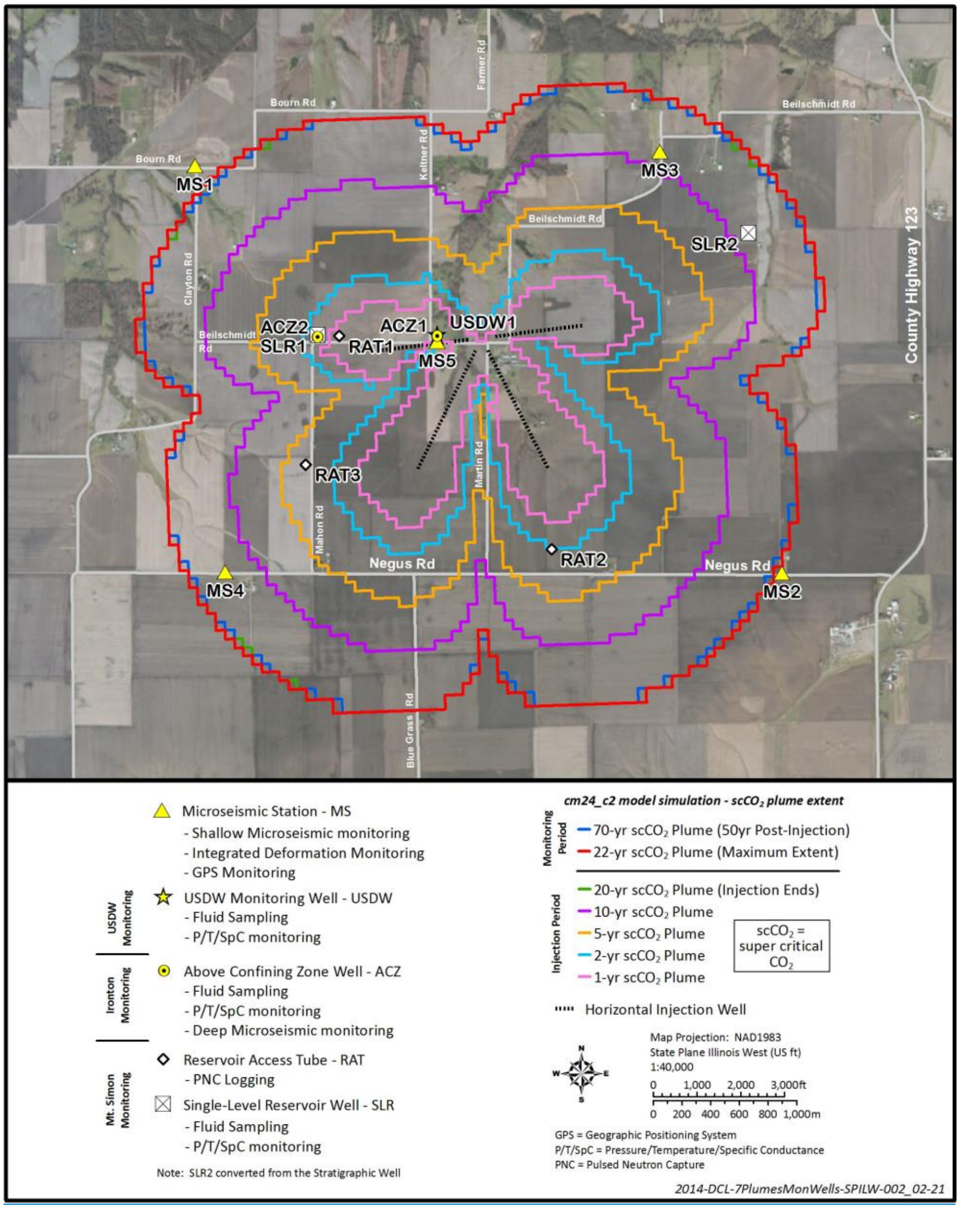


**Figure 1. Monitoring Network Layout and Predicted Plume Extents at Several Time Intervals**

## Carbon Dioxide Stream Analysis

FutureGen will conduct injection stream analysis to meet the requirements ~~at~~ of 40 CFR 146.90(a), as described below and in Section 5.2.4.2 of ~~their~~ its permit application.

*[From Section 5.2.4.2: Injection Stream Analysis Parameters]*

Based on the anticipated composition of the $CO_2$ stream, a list of parameters was identified for analysis (Chapter 4.0, Table 4.1). Samples of the $CO_2$ stream will be collected regularly (e.g., quarterly) for chemical analysis.

**Table 1. Parameters and Frequency for $CO_2$ Stream Analysis~~.~~**

| **Parameter/Analyte** | **Frequency** |
|---|---|
| ~~pH~~Pressure | ~~quarterly~~cContinuous |
| Temperature | ~~quarterly~~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 |

How will FutureGen measure the pH of the gas stream?

FutureGen Response: This may have been a cut-and-paste error; the table has been updated.

Sampling methods:

*[From Section 5.2.4.3: Sampling Method]*

Grab samples of the $CO_2$ stream will be obtained for analysis of gases, including $CO_2$, $O_2$, $H_2S$, Ar, and water moisture. Samples of the $CO_2$ stream will be collected from the $CO_2$ pipeline at a location where the material is representative of injection conditions. A sampling station will be installed in the ground or on a structure close to the pipeline and connected to the pipeline via ~~small-diameter stainless steel tubing~~ a sampling manifold with pressure and temperature (P/T) instrumentation to accommodate double-sided constant pressure sampling cylinders that will be used to collect the samples. ~~A pressure regulator will be used to reduce the pressure of the $CO_2$ to approximately 250 psi so that the $CO_2$ is in the gas state when collected rather than a supercritical liquid. Cylinders will be purged with sample gas (i.e., $CO_2$) prior to sample collection to remove laboratory-added helium gas and ensure a representative sample.~~The collection procedure is designed to collect and preserve representative $CO_2$ fluid samples from the pipeline to maintain pressure, phase, and constituent integrity and facilitate sample transport for analysis.

Analytical techniques: *[Not specified.]*

FutureGen Response: See FutureGen QASP.Section B.4.4 for analytical techniques for indirect $CO_2$ Measurement.

Laboratory to be used/chain-of-custody~~of custody~~ procedures: *[Not specified.]*FutureGen Response: See FutureGen QASP. Sections B.4.5 through B.4.7 for laboratory quality and Section B.1.3 for sample handling and custody.

Quality assurance and surveillance measures:

*[from Section 5.6: Data Management]*

A wide variety of monitoring data will be collected specifically for this project, under appropriate quality assurance protocols.

*[from Section 5.8: Quality Assurance and Surveillance Plan]*

Data quality assurance and surveillance protocols will be designed to facilitate compliance with requirements specified in 40 CFR 146.90(k).

A complete QASP will be needed.

FutureGen Response: See FutureGen QASP Sections A.9 for data management, B.1 for CO2 sampling and analysis, B.4 analytical techniques, chain of custody procedures..

## Continuous Recording of Injection Pressure, Rate, and Volume; Annulus Pressure

FutureGen will conduct continuous monitoring of injection parameter to meet the requirements ~~at~~ of 40 CFR 146.90(b), as described below and in Section 5.2.4 of ~~their~~ its permit application.

*[From Section 5.2.4.1: Continuous Monitoring of the CO2 Injection Process]*

### Continuous Recording of Injection Mass Flow Rate

The mass flow rate of $CO_2$ injected into the well field will be measured by a flow meter skid with a Coriolis mass flow transmitter for each well. Each meter will have analog output (Micro Motion Coriolis Flow and Density Meter Elite Series or similar). A total of six flow meters will be supplied, providing for two spare flow meters to allow for flow meter servicing and calibration. Valving will be installed to select flow meters for measurement and for calibration. A single flow prover will be installed to calibrate the flow meters, and piping and valving will be configured to permit the calibration of each flow meter. The flow transmitters will each be connected to a remote terminal unit (RTU) on the flow meter skid.

The RTU will communicate with the Control Center through the well annular pressure maintenance and monitoring system (WAPMMS) programmable logic controller (PLC) located at the injection well site. The flow rate into each well will be controlled using a flow-control valve located in the $CO_2$ pipeline associated with each well. The control system will be programmed to provide the desired flow rate into three of the four injection wells, with the one remaining well receiving the balance of the total flow rate.

### Continuous Recording of Injection Pressure

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

## Continuous Recording of Injection Temperature

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

*[From 1/17/2014 response]*

Mechanical strain gauges and thermocouples wires will be the primary monitoring devices for P/T and will be frequently recalibrated (initially on a quarterly basis). In some wells a redundant fiber-optic cable will also be installed as part of a comparison test with more standard gauges.

The injection wells will be completed with a string of 3.5 in.-OD tubing that extends from the wellhead at the surface to near the top of the perforated interval. A tubing string that is 4,000 ft long will extend approximately 11 ft below the top of the perforations. The tubing string will be held in place at the bottom by a packer that is positioned just above the uppermost perforations (approximate measured depth of 3,975 ft). An optical or 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 CO2 injection P/T inside the tubing at this depth. 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. In addition, injection P/T will also be continuously measured at the surface via real- time P/T instruments installed in the CO2 pipeline near the pipeline interface with the wellhead. The surface instruments will be checked, and if necessary, recalibrated or replaced on a regular basis (e.g., semi-annually) to ensure they are providing accurate data. Because the surface instruments can be more readily accessed and maintained than the bottom-hole gauge, they will be used to control injection operations and trigger shutdowns.

The sampling and recording protocol of the pressure and temperature gauges is needed from FutureGen in order to determine if the sampling protocols meet Region 5's guidance on continuous monitoring. Specific information on the frequency at which temperature and pressure data will measured is also needed.

FutureGen Response: The $CO_2$ injection stream will be continuously monitored at the surface for pressure, temperature, and flow, as part of the instrumentation and control systems for the FutureGen $CO_2$ Pipeline and Storage Project. Measurement frequency will be maintained at 10 minutes or less. The P/T will also be monitored within each injection well at a position located immediately above the injection zone at the end of the injection tubing. The downhole sensor will be the point of compliance for maintaining injection pressure below 90% of formation fracture pressure. If the downhole probe goes out between scheduled maintenance events then the surface pressure measurement coupled with the analytical code, CO2Flow, will be used to determine permit compliance downhole at the injection elevation. The CO2Flow program estimates pressure and fluid state evolution as $CO_2$ moves through pipelines and injection tubing and will be used to determine an equivalent downhole pressure.

## Corrosion Monitoring

FutureGen will conduct corrosion monitoring of well materials to meet the requirements of 40 CFR 146.90(c), as described below and in Section 5.3.2.2 of its permit application.

*[From Section 5.3.2.2: Corrosion Monitoring]*

### Casing and Tubing

Corrosion of well materials will be monitored using the corrosion coupon method. Corrosion monitoring of well casing and tubing materials will be conducted using coupons placed in the $CO_2$ pipeline. The coupons will be made of the same material as the long string of casing and the injection tubing. The coupons will be removed quarterly and assessed for corrosion using the 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.

Corrosion rate will be calculated as the weight loss during the exposure period divided by the duration (i.e., weight loss method).

Casing and tubing will also be evaluated periodically for corrosion throughout the life of the injection well by running casing inspection (wireline) logs. The frequency of running these tubing and casing inspection logs will be determined based on site-specific parameters and well performance. Wireline tools will be lowered into the well to directly measure properties of the well tubulars that indicate corrosion. Four types of wireline tools will be available for assessing corrosion of well materials—mechanical, electromagnetic, ultrasonic, and videographic. Mechanical, electromagnetic, and/or ultrasonic tools will be used primarily to monitor well corrosion (Table 2). These tools, or comparable tools from alternate vendors, will be used to monitor the condition of well tubing and casing.

**Table 2. Examples of Wireline Tools for Monitoring Corrosion of Casing and Tubing (Table 5.6 of FutureGen's Permit Application)**

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

(a) Schlumberger Limited

(b) Baker Hughes, Inc.

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

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

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

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

## Groundwater Quality Monitoring

FutureGen will conduct groundwater quality/geochemical monitoring above the confining zone to meet the requirements of 40 CFR 146.90(d). The following information is drawn from Sections 5.1.4 and 5.2.2 of FutureGen’s permit application, as well as the supplemental information submitted in January 2014.

**FutureGen will conduct periodic fluid sampling throughout the injection phase in three wells constructed for the purpose of this project: two ACZ monitoring wells in the Ironton Sandstone (the first permeable unit above the confining zone) and a lowermost USDW well in the St. Peter Sandstone. Details about these wells are in Table 3 and Figure 2 is a map with the well locations. The coordinates (in decimal degrees) of the wells are in Attachment A. Well construction information and well schematics are in Attachment B.**

**Table 3. Monitoring Wells to Be Used for GroundWater/Geochemical Sampling Above the Confining Zone**

| | Above Confining Zone (ACZ) | USDW |
|---|---|---|
| **Number of Wells** | 2 | 1 |
| **Total Depth (ft)** | 3,470 | 2,000 |
| **Lat/Long (WGS84)** | ACZ1: 39°48'01.24"N~~39.800400~~, 90°04'41.87"W~~-90.078344;~~<br>ACZ2: 39°48'01.06"N~~39.800353~~, 90°05'16.84"W~~-90.088064~~ | USDW1: 39°48'01.73"N~~39.800400~~, 90°04'41.87"W~~-90.078344~~ |
| **Monitored Zone** | Ironton Sandstone | St. Peter Sandstone |
| **Monitoring Instrumentation** | Fiber-optic (microseismic) cable cemented in annulus;<br>P/T/SpC probe in monitored interval* | P/T/SpC probe in monitored interval* |

* The P/T/SpC (pressure, temperature, specific conductance) probe is an electronic downhole multi-parameter probe incorporating sensors for measuring fluid P/T/SpC within the monitored interval. The probe is installed inside tubing string, which is perforated (slotted) over the monitoring interval. Sensor signals are multiplexed to a surface data logger through a single conductor wireline cable.

~~**Figure 1. Locations of ACZ and USDW wells relative to FutureGen's injection zone monitoring wells, injection wells, and predicted plume extent.**~~

~~Lat/Longs for the wells identified in Figure 1 should be tabulated on a separate page and placed as an attachment to the testing and monitoring plan template.~~

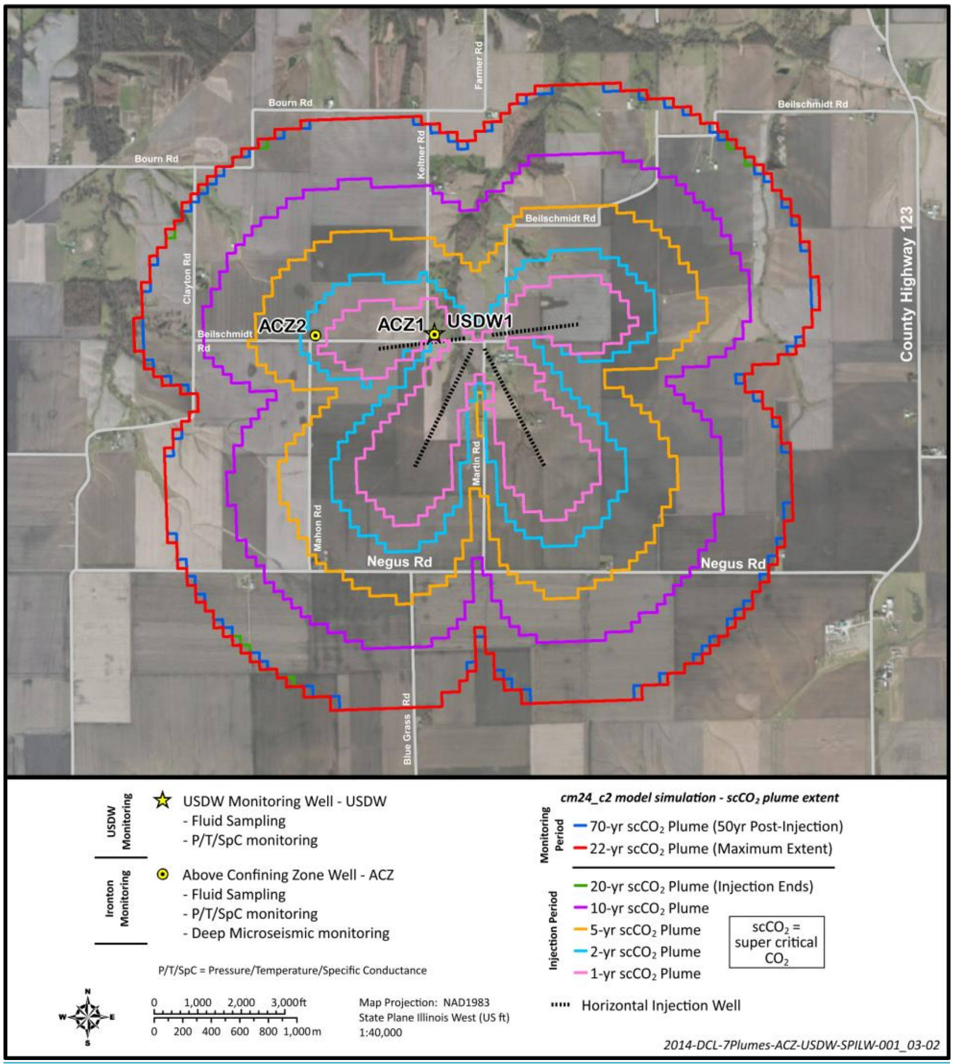
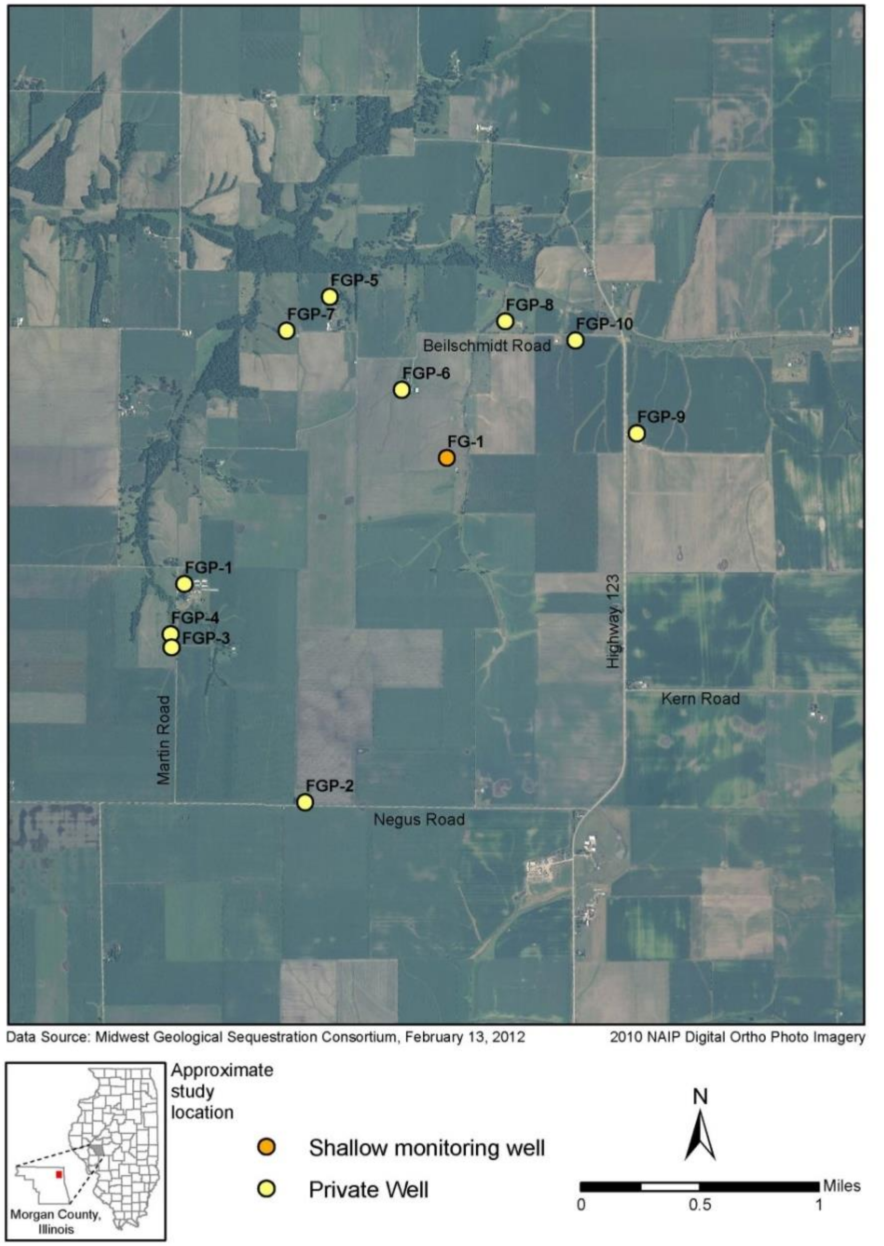


**Figure 2. ACZ and USDW Well Locations and Predicted Plume Extents at Several Time Intervals**

FutureGen will also conduct baseline sampling in the shallow, semi-consolidated glacial sediments that make up the surficial aquifer~~,~~. This sampling will use~~ing~~ ~~approximately~~ ~~10~~nine ~~local landowne~~ private water~~r~~ wells and one shallow monitoring well that has been drilled for the project (~~Figure 2~~Figure 3). The locations of the surficial aquifer monitoring wells are tabulated in Attachment C.



Data Source: Midwest Geological Sequestration Consortium, February 13, 2012

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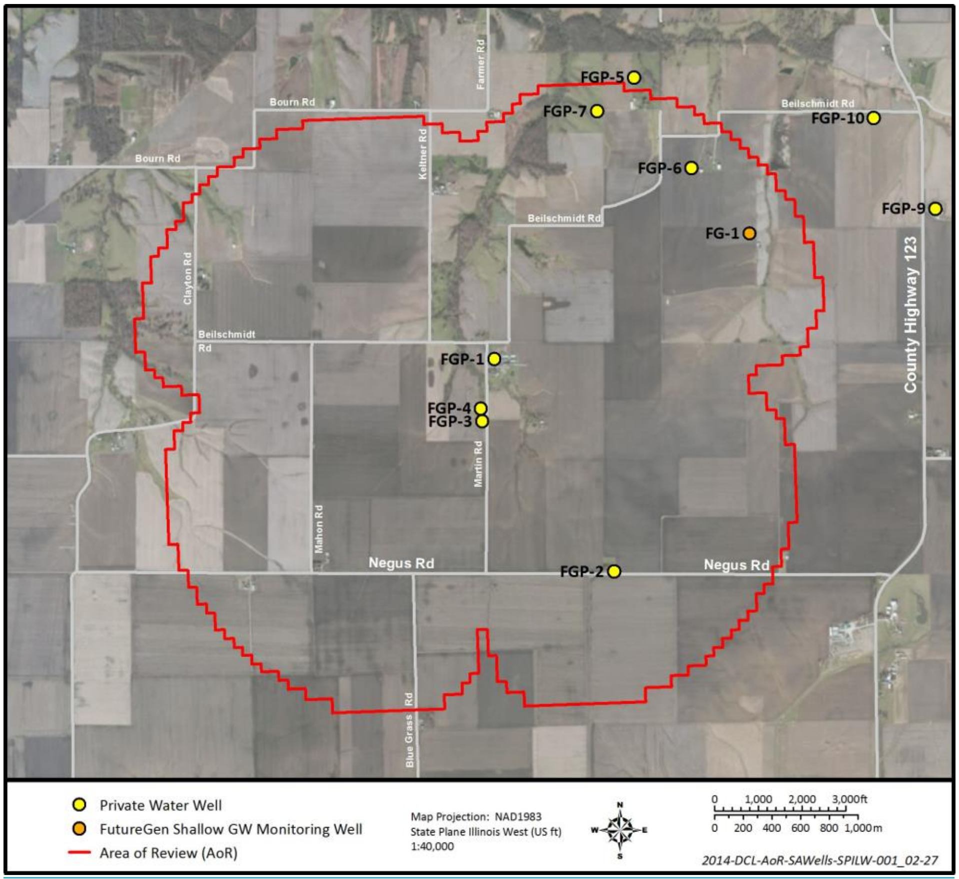

**Figure 3. Surficial Aquifer Monitoring Locations. Well FG-1 is a dedicated well drilled for the purposes of the FutureGen 2.0 Project. FGP-1 through FGP-10 are local landowners' wells.**

*[Adapted from the spreadsheet submitted on 1/29/14:]*

Sampling will take place at the frequencies specified in Table 4 (for the surficial aquifer), Table 5 (for the St. Peter), and Table 6 (for the Ironton). 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, but 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. Given our current conceptual understanding of the subsurface environment, early and appreciable impacts on near-surface environments are not expected, so extensive networks of surficial aquifer monitoring wells are not warranted.

Target parameters for the ACZ wells include pressure, temperature, and hydrogeochemical indicators of $CO_2$ and brine composition. A comprehensive suite of geochemical and isotopic analyses will be performed on collected fluid samples and analytical results will be used to characterize baseline geochemistry and provide a metric for comparison during operational phases. Selection of this initial analyte list was based on relevance for detecting the presence of fugitive brine and $CO_2$. Results for this comprehensive set of analytes will be evaluated and a determination made regarding which analytes to carry forward through the operational phases of the project. This selection process will consider the uniqueness and signature strength of each potential analyte and whether their characteristics provide for a high-value leak-detection capability. Once baseline conditions have been established, observed differences in the geochemical and isotopic signature between the reservoir and overlying monitoring intervals, along with predictions of leakage-related pressure response, will be used to specify trigger~~s~~ values that would prompt further action, including a detailed evaluation of the observed response and possible modification to the monitoring approach and/or storage site operations. This evaluation will be supported by numerical modeling of theoretical leakage scenarios that will be used to evaluate leak-detection capability and interpret any observed pressure and/or geochemical/isotopic change in the ACZ wells.

Target parameters for the USDW and surficial aquifer wells include pressure, temperature, and hydrogeochemical indicators of $CO_2$ and brine composition. A comprehensive suite of geochemical and isotopic analyses will be performed on collected fluid samples during the baseline monitoring period. Selection of this initial analyte list was based on relevance for detecting the presence of fugitive brine and $CO_2$. Results for this comprehensive set of analytes will then be evaluated and a determination made regarding which analytes to carry forward through the operational phases of the project. This selection process will consider the uniqueness and signature strength of each potential analyte and whether their characteristics provide for a high-value leak-detection capability. Trigger values for the lowermost USDW monitoring well and the surficial aquifer monitoring wells have not been defined. If a leakage response is observed in the ACZ early-detection monitoring wells (Ironton) then the decision not to institute USDW aquifer triggers will be reevaluated based on the magnitude of the observed leakage response and predictive simulations of $CO_2$ transport between the Ironton and the St. Peter aquifers.

Note: The information in the following tables is drawn from Tables 5.3, 5.4, and 5.5 of FutureGen's permit application, updated to reflect the most recent submissions. Tables 5.4 and of the permit application give a fairly comprehensive list of target parameters that are under consideration, including a brief description of sampling and analysis requirements. However, FutureGen has not yet submitted a final list of the planned parameters; see the text above. In particular, dissolved and/or separate-phase $CO_2$ is not listed as a target parameter under consideration in Tables 5.4 and 5.5, and this should be discussed further. Depending on the final suite of parameters chosen, it may be appropriate to monitor for $CO_2$ indirectly, e.g., by monitoring dissolved inorganic carbon concentrations in combination with pH as recommended by researchers such as Wilkin and Digiulio (2010). However, this determination will need to be made after the final list of parameters is received. |Reference: Wilkin, R.T. and D.C. Digiulio. 2010. Geochemical Impacts to Groundwater from Geologic Carbon Sequestration: Controls on pH and Inorganic Carbon Concentrations from Reaction Path and Kinetic Modeling. Environ. Sci. Technol. 44(12): 4821-4827.|

FutureGen Response: The target parameter tables below have been updated to reflect the final list of planned parameters that will be measured during baseline sampling. They include both dissolved gas compositional analysis (including $CO_2$) and measurements of dissolved inorganic carbon and pH.

### Table 4. Sampling Schedule for Surficial Aquifer Monitoring Wells

| **Monitoring well name/location/map reference:** Surficial aquifer monitoring wells (Figure 2)<br>**Well depth/formation(s) sampled:** Shallow glacial sediments (approx. 17 ft – 49 ft) | | |
|---|---|---|
| **Parameter/Analyte** | **Frequency (Baseline)** | **Frequency (Injection Phase)** |
| Dissolved or separate-phase $CO_2$ | ~~Not listed in Tables 5.4, 5.5~~At least 3 sampling events | None planned |
| ~~Pressure~~Water-level | At least 3 sampling events | None planned |
| Temperature | At least 3 sampling events | None planned |
| Other parameters, including total dissolved solids, pH, specific conductivity, major cations and anions, trace metals, dissolved inorganic carbon, total organic carbon, carbon and water isotopes, and radon | At least 3 sampling events | None planned |

### Table 5. Sampling Schedule for the USDW Monitoring Well

| **Monitoring well name/location/map reference:** One USDW monitoring well (see Figure 1)<br>**Well depth/formation(s) sampled:** St. Peter Sandstone (2,000 ft) | | |
|---|---|---|
| **Parameter/Analyte** | **Frequency (Baseline)** | **Frequency (Injection Phase)** |
| Dissolved or separate-phase $CO_2$ | At least 3 sampling events~~Not listed in Tables 5.4, 5.5~~ | Quarterly for 3 years, then semi-annually for 2 years and annually thereafter~~Not listed in Tables 5.4, 5.5~~ |
| Pressure | Continuous, 1 year minimum~~At least 3 sampling events~~ | ~~Quarterly for 3 years, then semi-annually for 2 years and annually thereafter~~Continuous |
| Temperature | Continuous, 1 year minimum~~At least 3 sampling events~~ | Continuous~~Quarterly for 3 years, then semi-annually for 2 years and annually thereafter~~ |
| Other parameters, including total dissolved solids, pH, specific conductivity, major cations and anions, trace metals, dissolved inorganic carbon, total organic carbon, carbon and water isotopes, and radon | At least 3 sampling events | Quarterly for 3 years, then semi-annually for 2 years and annually thereafter |

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### Table 6. Sampling Schedule for ACZ Monitoring Wells

| **Monitoring well name/location/map reference:** Two ACZ monitoring wells (see Figure 1)<br>**Well depth/formation(s) sampled:** Ironton Sandstone (3,470 ft) | | |
|---|---|---|
| **Parameter/Analyte** | **Frequency (Baseline)** | **Frequency (Injection Phase)** |
| Dissolved or separate-phase $CO_2$ | At least 3 sampling events~~Not listed in Tables 5.4, 5.5~~ | Quarterly for 3 years, then semi-annually for 2 years and annually thereafter~~Not listed in Tables 5.4, 5.5~~ |
| Pressure | Continuous, 1 year minimum~~At least 3 sampling events~~ | Continuous~~Quarterly for 3 years, then semi-annually for 2 years and annually thereafter~~ |
| Temperature | Continuous, 1 year minimum~~At least 3 sampling events~~ | Continuous~~Quarterly for 3 years, then semi-annually for 2 years and annually thereafter~~ |
| Other parameters, including total dissolved solids, pH, specific conductivity, major cations and anions, trace metals, | At least 3 sampling events | Quarterly for 3 years, then semi-annually for 2 years and annually thereafter |

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| | | |
|---|---|---|
| dissolved inorganic carbon, total organic carbon, carbon and water isotopes, and radon | | |

Sampling methods:

*[From Section 5.2.2.3: Sampling and Analysis]*

A sampling plan is referenced below, but not provided; also FutureGen cites cost as a factor in selecting methods – costs should not be a factor.

FutureGen response: The referenced plan is an activity specific work plan that will be developed just prior to sampling activities and thus it cannot be provided at this time. If the EPA would like to delete the reference to this plan, that would be fine. Cost would not be the basis of a decision regarding parameter measurements required by the rule, but it is used as a weighting criterion for supplemental analyses that FutureGen is considering carrying forward (e.g., if two analyses provide similar information and quality, then the cheaper method would be selected; isotopic analyses are expensive so they will only be carried forward if a significant benefit is demonstrated). If the EPA would prefer to remove this parenthetical, that would be fine.

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

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

Sampling and analytical techniques for target parameters are given in Table 7 and Table 8, respectively.

Note: We assume that FutureGen intends to test for all these parameters during the baseline sampling described above. However, clarification is needed. We will update these tables based on any further information submitted.

FutureGen Response: As discussed above, a comprehensive suite of geochemical and isotopic analyses will be performed on collected fluid samples and analytical results will be used to characterize baseline geochemistry and provide a metric for comparison during operational phases. Selection of this initial analyte list was based on relevance for detecting the presence of fugitive brine and $CO_2$. Results for this comprehensive set of analytes will be evaluated and a determination made regarding which analytes to carry forward through the operational phases of the project. This selection process will consider the uniqueness and signature strength of each potential analyte and whether their characteristics provide for a high-value leak-detection capability. Tables 7 and 8 have updated with the final analyte list.

**Table 7. Aqueous Sampling Requirements for Target Parameters (adapted from Table 5.4 of FutureGen's permit application)**

| Parameter | Volume/Container | Preservation | Holding Time |
|---|---|---|---|
| Major Cations: Al, Ba, Ca, Fe, K, Mg, Mn, Na, Si, | 20-mL plastic vial | Filtered (0.45 µm), $HNO_3$ to pH <2 | 60 days |
| Trace Metals: Sb, As, Cd, Cr, Cu, Pb, Se, Tl | 20-mL plastic vial | Filtered (0.45 µm), $HNO_3$ to pH <2 | 60 days |
| Cyanide (CN-) | 250-mL plastic vial | NaOH to pH > 12, 0.6 g ascorbic acid Cool 4°C, | 14 days |
| Mercury | 250-mL plastic vial | Filtered (0.45 µm), $HNO_3$ to pH <2 | 28 days |
| Anions: $Cl^-$, $Br^-$, $F^-$, $SO_4^{2-}$, $NO_3^-$ | 125-mL plastic vial | Filtered (0.45 µm), Cool 4°C | 45 days |
| Total and Bicarbonate Alkalinity (as $CaCO_3^{2-}$) | 100-mL HDPE | Filtered (0.45 µm), Cool 4°C | 14 days |
| Gravimetric Total Dissolved Solids (TDS) | 250-mL plastic vial | Filtered (0.45 µm), no preservation, Cool 4°C | 7 days |
| Water Density | 100-mL plastic vial | No preservation, Cool 4°C | |
| Total Inorganic Carbon (TIC) | 250-mL plastic vial | $H_2SO_4$ to pH <2, Cool 4°C | 28 days |
| Dissolved Inorganic Carbon (DIC) | 250-mL plastic vial | Filtered (0.45 µm), $H_2SO_4$ to pH <2, Cool 4°C | 28 days |
| Total Organic Carbon (TOC) | 250-mL amber glass | Unfiltered, $H_2SO_4$ to pH <2, Cool 4°C | 28 days |
| Dissolved Organic Carbon (DOC) | 125-mL plastic vial | Filtered (0.45 µm), $H_2SO_4$ to pH <2, Cool 4°C | 28 days |
| Volatile Organic Analysis (VOA) | Bottle set 1: 3-40-mL sterile clear glass vials<br>Bottle set 2: 3-40-mL sterile amber glass vials | Zero headspace, Cool <6 °C, Clear glass vials will be UV-irradiated for additional sterilization | 7 days |
| Methane | Bottle set 1: 3-40-mL sterile clear glass vials<br>Bottle set 2: 3-40-mL sterile amber glass vials | Zero headspace, Cool <6 °C, Clear glass vials (bottle set 1) will be UV-irradiated for additional sterilization | 7 days |
| Stable Carbon Isotopes $^{13/12}C$ ($\delta^{13}C$) of DIC in Water | 60-mL plastic or glass | Filtered (0.45 µm), Cool 4°C | 14 days |
| Radiocarbon $^{14}C$ of DIC in Water | 60-mL plastic or glass | Filtered (0.45 µm), Cool 4°C | 14 days |
| Hydrogen and Oxygen Isotopes $^{2/1}H$ ($\delta D$) and $^{18/16}O$ ($\delta^{18}O$) of Water | 60-mL plastic or glass | Filtered (0.45 µm), Cool 4°C | 45 days |
| Carbon and Hydrogen Isotopes ($^{14}C$, $^{13/12}C$, $^{2/1}H$) of Dissolved Methane in Water | 1-L dissolved gas bottle or flask | Benzalkonium chloride capsule, Cool 4°C | 90 days |
| Compositional Analysis of Dissolved | 1-L dissolved gas bottle | Benzalkonium chloride capsule, Cool | 90 days |

| Parameter | Volume/Container | Preservation | Holding Time |
|---|---|---|---|
| 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 $C_6$+) | or flask | 4°C | |
| Radon ($^{222}Rn$) | 1.25-L PETE | Pre-concentrate into 20-mL scintillation cocktail. Maintain groundwater temperature prior to pre-concentration | 1 day |
| pH | Field parameter | None | <1 h |
| Specific Conductance | Field parameter | None | <1 h |

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

**Table 8. Analytical Requirements (adapted from Table 5.5 of FutureGen’s permit application)**

| **Parameter** | **Analysis Method** | **Detection Limit or Range** | **Typical Precision/ Accuracy** | **QC Requirements** |
|---|---|---|---|---|
| Major Cations: Al, Ba, Ca, Fe, K, Mg,<br>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<br>Carbon analyzer, phosphoric acid digestion of TIC | 0.2 mg/L | ±20% | Quadruplicate analyses, daily calibration |
| Dissolved Inorganic Carbon (DIC) | SW846 9060A or equivalent<br>Carbon analyzer, phosphoric acid digestion of DIC | 0.2 mg/L | ±20% | Quadruplicate analyses, daily calibration |
| Total Organic Carbon (TOC) | SW846 9060A or equivalent<br>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<br>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<br>Purge and Trap GC/MS | 0.3 to 15 µg/L | ±20% | Blanks, LCS, spike, spike duplicates per batch of 20 |
| Methane | RSK 175 Mod<br>Headspace GC/FID | 10 µg/L | ±20% | Blanks, LCS, spike, spike duplicates per batch of 20 |
| Stable Carbon Isotopes $^{13/12}C$ ($1^{13}C$) of DIC in Water | Gas Bench for $^{13/12}C$ | 50 ppm of DIC | ±0.2p | Duplicates and working standards at 10% |
| Radiocarbon $^{14}C$ of DIC in Water | AMS for $^{14}C$ | Range: 0 i 200 pMC | ±0.5 pMC | Duplicates and working standards at 10% |

| Parameter | Analysis Method | Detection Limit or Range | Typical Precision/ Accuracy | QC Requirements |
|---|---|---|---|---|
| Hydrogen and Oxygen Isotopes $^{2/1}$H (δ ) and $^{18/16}$O (1$^{18}$O) of Water | CRDS $H_2O$ Laser | Range: -500‰ to 200‰ vs. VSMOW | $^{2/1}$H: ±2.0‰<br>$^{18/16}$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<br>$^{13}$C: ±0.2‰<br>$^{2/1}$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 compon-ent | 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

| ~~Parameter~~ | ~~Analysis Method~~ | ~~Detection Limit or Range~~ | ~~Typical Precision/ Accuracy~~ | ~~QC Requirements~~ |
|---|---|---|---|---|
| ~~Major Cations: Al, Ba, Ca, Fe, K, Mg, Mn, Na, Si,~~ | ~~ICP-OES, PNNL-AGG-ICP-AES (similar to EPA Method 6010B)~~ | ~~0.1 to 1 mg/L (analyte dependent)~~ | ~~±10%~~ | ~~Daily calibration; blanks and duplicates and matrix spikes at 10% level per batch of 20~~ |
| ~~Trace Metals: Sb, As, Ba, Cd, Cr, Cu, Pb, Hg, Se, Tl~~ | ~~ICP-MS, PNNL-AGG-415 (similar to EPA Method 6020)~~ | ~~1 µg/L for trace elements~~ | ~~±10%~~ | ~~Daily calibration; blanks and duplicates and matrix spikes at 10% level per batch of 20~~ |
| ~~Anions: Cl$^-$, Br$^-$, F$^-$, SO4$^{2-}$, NO$_3^-$, CO$_3^{2-}$~~ | ~~Ion Chromatography, AGG-IC-001 (based on EPA Method 300.0A)~~ | | ~~±15%~~ | ~~Daily calibration; blanks and duplicates at 10% level per batch of 20~~ |
| ~~TDS~~ | ~~Gravimetric Method Standard Methods 2540C~~ | ~~12 mg/L~~ | ~~± 5%~~ | ~~Balance calibration, triplicate samples~~ |
| ~~Water Density~~ | ~~Standard Methods 227~~ | ~~0.0001 g/mL~~ | ~~±0.0%~~ | ~~Triplicate measurements~~ |
| ~~Alkalinity~~ | ~~Titration, standard methods 102~~ | ~~4 mg/L~~ | ~~±3 mg/L~~ | ~~Triplicate titrations~~ |

| | | | | |
|---|---|---|---|---|
| ~~Dissolved Inorganic Carbon (DIC)~~ | ~~Carbon analyzer, phosphoric acid digestion of DIC~~ | ~~0.002%~~ | ~~±10%~~ | ~~Triplicate analyses, daily calibration~~ |
| ~~Total Organic Carbon (TOC)~~ | ~~Carbon analyzer; total carbon by 900°C pyrolysis minus DIC = TOC~~ | ~~0.002%~~ | ~~±10%~~ | ~~Triplicate analyses, daily calibration~~ |
| ~~Carbon Isotopes ($^{14/12}$C, $^{13/12}$C)~~ | ~~Accelerator MS~~ | ~~$10^{-15}$~~ | ~~±4‰ for $^{14}$C;~~<br>~~±0.2‰ for $^{13}$C~~ | ~~Triplicate analyses~~ |
| ~~Water Isotopes ($^{2}$H/$^{1}$H, $^{18/16}$O)~~ | ~~Water equilibration coupled with IRMS ; Aalternatively, consider WS-CRDS~~ | ~~$10^{-9}$~~ | ~~IRMS: ±1.0‰ for $^{2}$H; ±0.15‰ for $^{18}$O;~~<br>~~WS-CRDS: ±0.10‰ for $^{2}$H; ±0.025‰ for $^{18}$O~~ | ~~Triplicate analyses~~ |
| ~~Radon ($^{222}$Rn)~~ | ~~Liquid scintillation after pre-concentration~~ | ~~5 mBq/L~~ | ~~±10%~~ | ~~Triplicate analyses~~ |
| ~~Naphthalene Sulfonate **or** Benzoic Acid Tracer (aqueous phase)~~ | ~~Liquid chromatography–mass spectrometry (LC-MS) **or** gas chromatography with electron capture detector (ECD)~~ | ~~5 parts per trillion (5 x $10^{12}$) **or** 10 parts per quadrillion (10 x $10^{15}$)~~ | ~~Varies with conc.,±30% at detection limit~~ | ~~Duplicates 10% of samples, significant number of blanks for cross-contamination~~ |
| ~~Perfluorocarbon Tracer (PFT) (scCO$_2$ or gas phase)~~ | ~~Gas chromatography with electron capture detector (ECD)~~ | ~~10 parts per quadrillion (10 x $10^{15}$)~~ | ~~Varies with conc., ±30% at detection limit~~ | ~~Duplicates 10% of samples, significant number of blanks for cross-contamination~~ |
| ~~pH~~ | ~~pH electrode~~ | ~~2 to 12 pH units~~ | ~~±0.2 pH unit~~<br>~~For indication only~~ | ~~User calibrate, follow manufacturer recommendations~~ |
| ~~Specific conductance~~ | ~~Electrode~~ | ~~0 to 100 mS/cm~~ | ~~±1% of reading For indication only~~ | ~~User calibrate, follow manufacturer recommendations~~ |
| ~~Temperature~~ | ~~Thermocouple~~ | ~~5 to 50°C~~ | ~~±0.2°C~~<br>~~For indication only~~ | ~~Factory calibration~~ |

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

Laboratory to be used/chain-of-custody procedures:

*[from Section 5.2.2.3 Sampling and Analysis]*

[S]amples will be tracked using appropriately formatted chain-of-custody forms.

FutureGen lacks detail in its description of laboratory and chain-of-custody procedures. FutureGen should provide a more detailed Testing and Monitoring Plan containing this information. [Request from FutureGen.]

FutureGen Response: See FutureGen QASP Sections B.4.3 thru B.4.7.

Quality assurance and surveillance measures:

*[from Section 5.8: Quality Assurance and Surveillance Plan]*

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

FutureGen lacks detail in its description of quality assurance and surveillance protocols. FutureGen should provide a more detailed Testing and Monitoring Plan containing this information. [Request from FutureGen.]

FutureGen Response: See FutureGen QASP.Sections B.6 thru B.11 for specifics concerning geophysical monitoring procedures.

Plan for guaranteeing access to all monitoring locations:

*[Adapted from the spreadsheet submitted on 1/29/14:]*

The locations of the ACZ and USDW wells have been finalized, pending final signing of landowner agreements. For these wells, the land will either be purchased or leased for the life of the project, so access will be secured.

Access to the surficial aquifer wells will not be required over the lifetime of the project. Access to wells for baseline sampling has been on a voluntary basis by the well owner. Ten local landowners originally agreed to have their surficial aquifer wells sampled, one opted out during a recent sampling event.

## External Mechanical Integrity Testing

FutureGen will conduct external mechanical integrity testing to meet the requirements of 40 CFR 146.90(e), as described below and in Section 5.3.2 of its permit application.

Note: the discussion of MITs in the permit application appears to describe the purpose of MITs and background, but does not describe the actual tests FutureGen will perform (we retain it for now). Additional information is needed for the Testing and Monitoring Plan; a table outlining the MITs and a schedule for performing them is recommended.

FutureGen response: Updated MIT information is provided in Section 8.3 of the Advanced Design document (text is inserted below).

During the 20-year operational (i.e., injection) period, maintenance will be performed on the injection wells to ensure they are in working condition. These activities include conducting annual mechanical integrity tests (MITs) to comply with the UIC Class VI regulation and regular (e.g., quarterly) preventive maintenance (e.g., lubricating) of the wellhead valves. To satisfy the annual MIT requirement, a ~~pulsed-neutron capture (~~PNC logging tool will be run in each injection well once per year to look for evidence of upward $CO_2$ migration out of the $CO_2$ storage zone. The PNC logging tool will be run twice during each event: once in the gas-view mode to detect $CO_2$ and once in the oxygen-activation mode to detect water. A temperature log will also be collected in conjunction with each PNC logging run. Because the primary purpose of the external MIT is to demonstrate that there is no upward leakage of fluid out of the storage zone, the PNC logging tool will be run to a depth greater than the bottom of the caprock. Because the injection tubing will extend to a depth below the caprock, the PNC logs will be run inside tubing; therefore, it will not be necessary to remove the injection tubing to conduct the PNC logging. Based on the following excerpt from the Class VI UIC regulation, these logs should satisfy the annual external MIT requirement: "*(c) At least once per year, the owner or operator must use one of the following methods to determine the absence of significant fluid movement under paragraph (a)(2) of this section: (1) An approved tracer survey such as an oxygen-activation log; or (2) A temperature or noise log.*" It is estimated that the annual maintenance events, including conducting the PNC logging and performing wellhead valve replacement will take approximately 10 work days, assuming the work is conducted working 12 hr/d. A preliminary schedule for the annual well maintenance event is provided in Table 9.

**Table 9. Schedule for Annual Injection Well Maintenance – per Well (preliminary)**

| Activity | Work Days | Cum. Days |
|---|---|---|
| Shut down injection, isolate surface system | 1 | 1 |
| Allow well to sit undisturbed for 24 hours | 1 | 2 |
| Conduct PNC logging (external MIT) | 2 | 4 |
| Kill well | 2 | 6 |
| Slickline set plug in tubing above packer | 0.5 | 6.5 |
| Disconnect $CO_2$ pipeline, instruments, and other lines; remove Christmas tree valves for maintenance or replacement | 0.5 | 7 |
| Reinstall Christmas tree valves, re-connect $CO_2$ pipeline, instruments, and other lines | 1 | 7 |
| Slickline pull plug from packer | 1 | 9 |
| Perform annular pressure test, internal MIT | 1 | 10 |
| Return well to service | 1 | 10 |

MIT = mechanical integrity test; PNC = pulsed-neutron capture.

~~Mechanical integrity~~ MITs are also required to demonstrate that there are no significant leaks in the casing, tubing, or packer. This requirement will be met by continuously monitoring injection pressure on the annulus between tubing and long-string casing and annulus fluid volume. These functions will be provided by the Annular Pressurization System (APS), which is discussed in Section **Error! Reference source not found.** of this document. Therefore, no additional testing is necessary to meet this requirement. Other tests that may be required by the EPA—for example a casing inspection log—have not been included in the cost estimate because it is uncertain whether additional tests will be required. Maintenance requirements specific to the APS are also discussed in Section **Error! Reference source not found.** of this document.

It is also anticipated that it will be necessary to replace selected well components throughout the 20-year injection period, although the identity of the components and their frequency of replacement cannot be determined a priori. However, the components most likely to require replacement include the wellhead valves (selected portions), the tubing string, the packer, and the bottom-hole P/T gauge and associated cable. A replacement frequency of 1 year was assumed for the wellhead valves (selected portions) in the cost estimate and a replacement frequency of 5 years was assumed for the downhole components (i.e., tubing, packer, and P/T gauge and associated cable). Because of the need to replace downhole equipment during the 5-year events, this results in a longer-duration workover for the 5-year events. It is estimated that these maintenance events will take approximately 21 work days, assuming the work is conducted working 12-hour shifts 7 d/wk. A preliminary schedule for the 5-year well maintenance event is provided in Table 10.

**Table 10. Schedule for 5-Year Injection Well Maintenance Events – per Well (preliminary).**

| Activity | Work Days | Cum. Days |
|---|---|---|
| Shut down injection, disassemble surface system | 1 | 1 |
| Arrive onsite with equipment rig-up/set-up | 3 | 4 |
| Conduct PNC logging (external MIT) | 2 | 6 |
| Kill well | 2 | 8 |
| Slickline set plug in tubing above packer | 0.5 | 8.5 |
| Disconnect $CO_2$ pipeline, instruments, and other lines; remove Christmas tree valves for maintenance or replacement | 0.5 | 9 |
| Pull tubing and P/T gauge and cable | 1.5 | 10.5 |
| Trip back in to pull packer | 0.5 | 11 |
| Pull packer | 0.5 | 11.5 |
| Reinstall new packer w/ plug, trip out to get P/T gauge and cable | 1.5 | 13 |
| Reinstall new P/T gauge and cable and injection tubing | 1.5 | 14.5 |
| Reinstall Christmas tree valves, re-connect $CO_2$ pipeline, instruments, and other lines. | 1.5 | 16 |
| Slickline pull plug from packer | 1 | 17 |
| Rig down and demobilize | 3 | 20 |
| Perform annular pressure test, internal MIT | 1 | 21 |
| Return well to service | 1 | 22 |

## Temperature Logging

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

Injection of $CO_2$ will have a cooling or heating effect on the natural temperature in the storage reservoirs, depending on the temperature of the injected $CO_2$ and other factors. Once injection starts, the flowing temperature will stabilize quickly (assuming conditions remain steady).

When an injection well is shut-in for temperature logging, the well bore fluid begins to revert toward ambient conditions. Zones that have taken injectate, either by design or not, will exhibit a “storage” signature on shut-in temperature surveys (storage signatures are normally cold anomalies in deeper wells, but may be cool or hot depending on the temperature contrast between the injectate and the reservoir). Losses behind pipe from the injection zone can be detected on both flowing and shut-in temperature surveys and exhibit a “loss” signature.

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

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

### Pulsed-Neutron Capture Logging

PNClogging will be used to quantify the flow of water in or around a borehole. For purposes of demonstrating external mechanical integrity, a baseline PNC log 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 PNC 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 PNC logging (EPA 2008) when performing this test.

Suggested language: Proposed external MIT procedures will be submitted to the EPA Region 5 office for review at least 30 days before any anticipated test. The permittee will work with the EPA Region 5 office to accommodate any comments it may have about the proposed test procedures.

*[from Section 5.3.2: Mechanical Integrity Testing During Service Life of Well]*

As discussed in the Construction and Operations Plan (Section 4.3), 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.

*[from Section 5.3.2.2*: *Corrosion Monitoring]*

Note that cement evaluation beyond the preliminary cement-bond log is not required for Class VI wells under MIT or corrosion monitoring (40 CFR 146.89 and 146.90). However, it is recognized that cement integrity over time can influence the mechanical integrity of an injection well. Therefore, cement-evaluation logs will be run when tubing is removed from the well (i.e., during well workovers).

## Pressure Fall-Off Testing

FutureGen will conduct pressure fall-off testing to meet the requirements of 40 CFR 146.90(f), as described below and in Section 5.3.1 of its permit application.

Note: the discussion of fall-off testing in the permit application appears to describe the purpose **of the tests and background, but does not describe the actual tests FutureGen will perform (we** retain it for now) or the frequency. Additional information is needed for the Testing and Monitoring Plan.

*[from Section 5.3.1*: *Pressure Fall-Off Testing]*

Pressure fall-off tests conducted after the start of $CO_2$ injection operations will provide the following information:

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

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

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

*[from Section 5.8: Quality Assurance and Surveillance Plan]*

Data QA and surveillance protocols adopted by the project will be designed to facilitate compliance with the requirements specified in 40 CFR 146.90(k). QA requirements for direct measurements within the injection zone, above the confining zone, and within the shallow USDW aquifer that are critical to the MVA program (e.g., pressure and aqueous concentration measurements) are covered in Sections 5.2.2 and 5.2.3 above. QA requirements for selected geophysical methods, which provide indirect measurements of $CO2$ nature and extent and are being tested for their applicability under site conditions, are not addressed in this plan. These measurements will be performed based on best industry practices and the QA protocols recommended by the geophysical services contractors selected to perform the work. Additional information is needed.

FutureGen Response: See FutureGen QASP. Section B.6 for details on pressure fall-off testing.

## Carbon Dioxide Plume and Pressure-Front Tracking

FutureGen will conduct direct and indirect ~~carbon dioxide~~$CO_2$ plume and pressure-front monitoring to meet the requirements of 40 CFR 146.90(g). The following information is drawn from Sections 5.1.4 and 5.2.3 of FutureGen's permit application and the additional information submitted in January 2014.

The following describes FutureGen's planned monitoring well network for plume and pressure- front monitoring (monitoring wells used for monitoring above the confining zone are described above in the Groundw~~W~~ater Quality Monitoring section).

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*[Adapted from 1/17/2014 submission]*

The design to be used for plume and pressure-front ~~tracking~~ monitoring in the injection zone is as follows:

- **Two ~~single-level in-reservoir (~~SLR~~)~~ wells** (one of which is a reconfiguration of the previously drilled stratigraphic well). These wells will be used to monitor within the injection zone beyond the east and west ends of the horizontal $CO_2$-injection laterals.

Monitored parameters: pressure, temperature, and hydrogeochemical indicators of $CO_2$. To meet permit requirements for pressure front monitoring, at least one additional SLR well will be installed outside the lateral extent of the $CO_2$ plume but within the lateral extent of the defined pressure front AoR. This well will be installed within 5 years of the start of injection.

- **Three RAT wells.** These are fully cased wells, which support PNC logging. The wells will not be perforated to preclude $CO_2$ flooding of the borehole, which can distort the $CO_2$ saturation measurements.

Monitored parameters: quantification of $CO_2$ saturation across the reservoir and caprock.

Details about these wells are provided in Table 11 and Figure 4 is a map with the well locations. The coordinates (in decimal degrees) of the wells are provided in Attachment A. Well construction information and well schematics are provided in Attachment B.~~Details on these wells are given in Table 9 and a map of the well locations is shown in Figure 3. Construction information has not yet been submitted.~~

**Table 11. Monitoring Wells to Be Used for Plume and Pressure-Front Monitoring**

| | **Single-Level In-Reservoir (SLR)** | **Reservoir Access Tube (RAT)** |
|---|---|---|
| **Number of Wells** | 2 | 3 |
| **Total Depth (ft)** | 4,150 | 4,465 |
| **Lat/Long (~~decimal degrees~~WGS84)** | SLR1: 39°48'01.56"N~~39.800353,~~ 90°05'16.84"W~~-90.088064; 39.806800, -90.052972~~SLR2: 39°48'24.51"N, 90°03'10.73"W | ~~39.800339, -90.086269; 39.791164, -90.089003~~RAT1: 39°48'01.28"N, 90°05'10.59"W<br>RAT2: 39°47'13.09"N, 90°04'08.50"W<br>RAT3: 39°47'32.25"N, 90°05'20.46"W |
| **Monteonitored Zone** | Mount Simon Sandstone | Mount Simon Sandstone |
| **Monitoring Instrumentation**~~**Monitoring Instrumentation**~~**Mon**~~**itoring**~~ Instrumentation | Fiber-optic P/T (tubing conveyed)*<br>P/T/SpC probe in monitored interval** | Pulsed-neutron capture logging equipment |

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* Fiber-optic cable attached to the outside of the tubing string, in the annular space between the tubing and casing.

** The P/T/SpC (pressure, temperature, specific conductance) probe is an electronic downhole multi-parameter probe incorporating sensors for measuring fluid P/T/SpC within the monitored interval. The probe is installed inside tubing string, which is perforated (slotted) over the monitoring interval. Sensor signals are multiplexed to a surface data logger through a single conductor wireline cable.

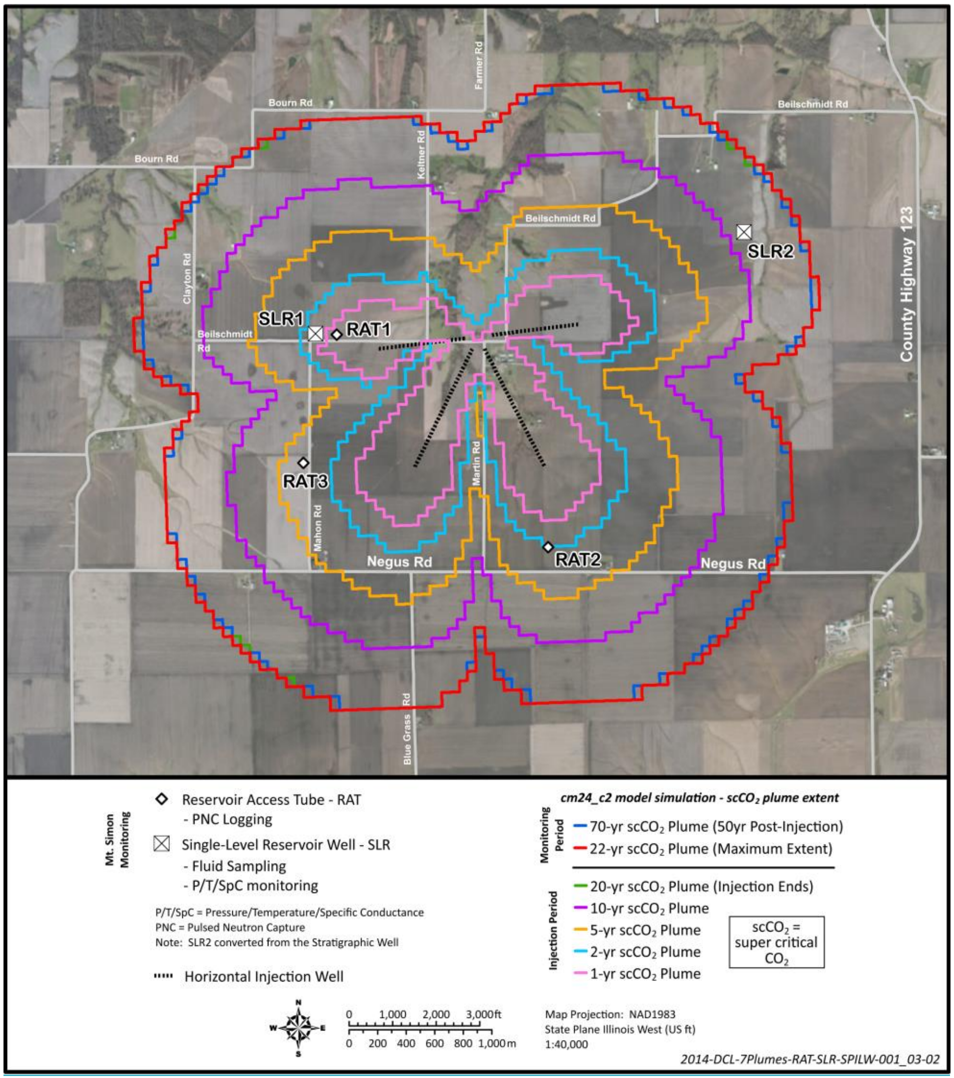

**Figure 4. RAT and SLR Well Locations and Predicted Plume Extents at Several Time Intervals**

**Direct Pressure Monitoring**

FutureGen will conduct direct pressure-front monitoring to meet the requirements of 40 CFR 146.90(g)(1). The following information is drawn from Section 5.2.3 of FutureGen's permit application and the additional information submitted in January 2014.

*[From Section 5.2.3.3: Pressure Monitoring]*Continuous monitoring of injection zone ~~pressure and temperature~~P/T will be performed with sensors installed in wells that are completed in the injection zone. ~~Pressure and temperature~~P/T monitoring in the injection well and all monitoring wells will be performed using a real-time monitoring system with surface readout capabilities so that pressure gauges do not have to be removed from the well to retrieve data. Power for the injection well will be provided by a dedicated line power supply. Power for all monitoring wells will be provided by a stand-alone solar array with battery backup so that a dedicated power supply to these more distal locations is not required.

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

- High-quality (high-accuracy, high-resolution) gauges with low drift characteristics will be used.
- Gauge components (gauge, cable head, cable) will be manufactured of materials designed to provide a long life expectancy for the anticipated downhole conditions.
- Upon acquisition, a calibration certificate will be obtained for every pressure gauge. The calibration certificate will provide the manufacturer's specifications for range, accuracy (% full scale), resolution (% full scale), ~~and~~ drift (< psi per year), and calibration results for each parameter. The calibration certificate will also provide the date that the gauge was calibrated and the methods and standards used.
- Gauges will be installed above any packers so they can be removed if necessary for recalibration by removing the tubing string. Redundant gauges may be run on the same cable to provide confirmation of downhole ~~pressure and temperature~~ P/T.
- Upon installation, all gauges will be tested to verify they are functioning (reading/transmitting) correctly.
- Pressure gauges that are used for the purpose of direct pressure monitoring will be calibrated on an annual basis with current annual calibration certificates kept on file with the monitoring data. In lieu of removing the injection tubing, the calibration of downhole pressure gauges will demonstrate accuracy by using a 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 all annual calibration checks (using the second calibrated gauge method described above) developed for the downhole gauge, may be used for the purpose of direct pressure monitoring. If used, these calibration curves, showing all historic pressure deviations, will be kept on file with the monitoring data.
- Gauges will be pulled and recalibrated whenever a workover occurs that involves removal of tubing. A new calibration certificate will be obtained whenever a gauge is recalibrated.

*[From 1/17/2014 submission]*

The injection wells will be completed with a string of 3.5 in.-OD tubing that extends from the wellhead at the surface to near the top of the perforated interval. A tubing string that is 4,000 ft long will extend approximately 11 ft below the top of the perforations. The tubing string will be held in place at the bottom by a packer that is positioned just above the uppermost perforations (approximate measured depth of

3,975 ft). An optical or 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. In addition, 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 surface instruments will be checked, and if necessary, recalibrated or replaced on a regular basis (e.g., semi-annually) to ensure they are providing accurate data. Because the surface instruments can be more readily accessed and maintained than the bottom-hole gauge, they will be used to control injection operations and trigger shutdowns.

*[From the spreadsheet submitted 1/29/14]*

Once the reservoir model has been updated with detailed site-specific information from the injection site, predictive simulations of pressure response will be generated for each SLR monitoring well. These predicted responses will be compared with monitoring results throughout the operational phase of the project and significant deviation in observed response would result in further action, including a detailed evaluation of the observed response, calibration/refinement of the numerical model, and possible modification to the monitoring approach and/or storage site operations. Preliminary predictions of pressure response at the two SLR and ACZ wells, based on the numerical model developed for the UIC permit application, are provided in Figure 5.

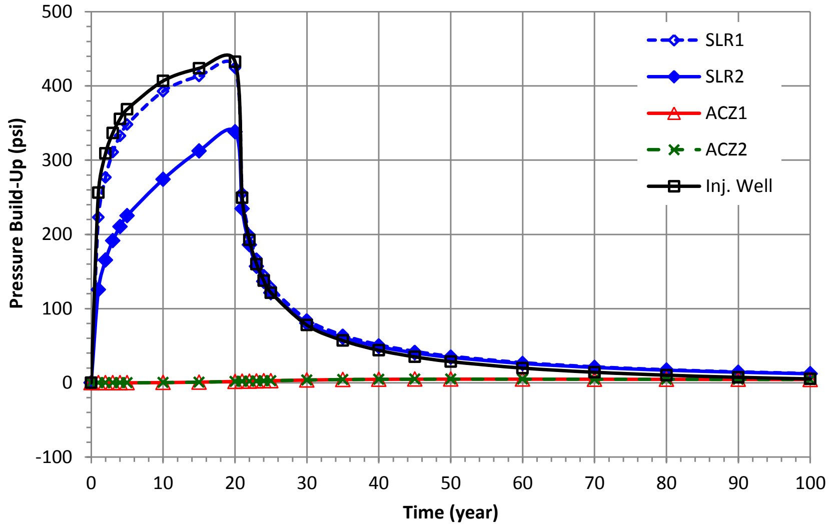

**Figure 5. Aqueous Pressure Build-Up Time-Course at the Monitoring and Injection Wells**

Direct pressure monitoring in the injection zone will take place as indicated in Table 12.

**Table 12. Monitoring Schedule for Direct Pressure-Front Tracking**

| Well Location/Map Reference | Depth(s)/Formation(s) | Frequency (Baseline) | Frequency (Injection Phase) |
|---|---|---|---|
| Injection Well 1 | Mount Simon/4,030 ft. | Continuous | Continuous |
| Injection Well 2 | Mount Simon/4,030 ft. | Continuous | Continuous |
| Injection Well 3 | Mount Simon/4,030 ft. | Continuous | Continuous |
| Injection Well 4 | Mount Simon/4,030 ft. | Continuous | Continuous |
| Two single-level monitoring wells (SLR Wells 1 and 2) | Mount Simon/4,150 ft. | Continuous | Continuous |

Quality assurance and surveillance measures:

*[from Section 5.8: Quality Assurance and Surveillance Plan]*

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

FutureGen lacks detail in its description of quality assurance and surveillance protocols. FutureGen should provide a more detailed Testing and Monitoring Plan containing this information. [Request from FutureGen.]

FutureGen Response: See FutureGen QASP Section B.7 for further discussion of pressure monitoring.

Plan for guaranteeing access to all monitoring locations:

*[From the spreadsheet submitted 1/29/14]*

The location of these wells has been finalized, pending final signing of landowner agreements. The land will either be purchased or leased for the life of the project, so access will be secured.

### Direct Geochemical Plume Monitoring

FutureGen will conduct direct $CO_2$ plume monitoring to meet the requirements of 40 CFR 146.90(g)(1). The following information is drawn from Section 5.2.3 of FutureGen's permit application and the additional information submitted in January 2014.

Fluid samples will be collected from monitoring wells completed in the injection zone before, during, and after $CO_2$ injection. The samples will be analyzed for chemical parameter changes that are indicators of the presence of $CO_2$ and/or reactions caused by the presence of $CO_2$. Direct fluid sampling in the injection zone will take place as indicated in Table 13.

**Table 13. Monitoring Schedule for Direct Geochemical Plume Monitoring**

| |
|---|
| **Monitoring well name/location/map reference:** Two SLR monitoring wells (see Figure 4) |

| **Well depth/formation(s) sampled:** Mount Simon Sandstone (4,150 ft) | | |
|---|---|---|
| **Parameter/Analyte** | **Frequency (Baseline)** | **Frequency (Injection Phase)** |
| Dissolved or separate-phase $CO_2$ | At least 3 sampling events | Quarterly for 3 years, then semi-annually for 2 years and annually thereafter |
| Pressure | Continuous, 1 year minimum~~At least 3 sampling events~~ | Continuous~~Quarterly for 3 years, then semi-annually for 2 years and annually thereafter~~ |
| Temperature | Continuous, 1 year minimum~~At least 3 sampling events~~ | Continuous~~Quarterly for 3 years, then semi-annually for 2 years and annually thereafter~~ |
| Other parameters, including major cations and anions, selected metals, general water-quality parameters (pH, alkalinity, total dissolved solids, specific gravity), and any tracers added to the $CO_2$ stream | At least 3 sampling events | Quarterly for 3 years, then semi-annually for 2 years and annually thereafter |

Sampling methods:

*[Adapted from Section 5.2.3.4: Aqueous Monitoring]*

Periodically, fluid samples will be collected from the monitoring wells completed in the injection zone. Fluid samples will be collected using an appropriate method to preserve the fluid sample at injection zone temperature and pressure conditions. Examples of appropriate methods include using a bomb-type sampler (e.g., Kuster sampler) after pumped or swabbed purging of the sampling interval, using a Westbay sampler, or using a pressurized U-tube sampler (Freifeld et al. 2005). These types of pressurized sampling methods are needed to collect the two-phase fluids (i.e., aqueous and $scCO_2$ solutions) for measurement of the percent water and $CO_2$ present at the monitoring location. Fluid samples will be analyzed for parameters that are indicators of $CO_2$ dissolution (Table 14), including major cations and anions, selected metals, general water- quality parameters (pH, alkalinity, total dissolved solids [TDS], specific gravity), and any tracers added to the $CO_2$ stream. Changes in major ion and trace element geochemistry are expected in the injection zone, but the arrival of proposed fluorocarbon or sulfonate tracers (co-injected with the $CO_2$) should provide an improved early-detection capability, because these compounds can be detected at 3 to 5 orders of magnitude lower relative concentration. Analysis of carbon and oxygen isotopes in injection zone fluids and the injection stream ($^{13/12}C$, $^{18/16}O$) provides another potential supplemental measure of $CO_2$ migration. Where stable isotopes are included as an analyte, data quality and detectability will be reviewed throughout the active injection phase and discontinued if these analyses provide limited benefit.

Sampling and analytical techniques for target parameters are given in Table 14 and Table 15, respectively.

Note: Section 5.2.3.4 indicates that all parameters in Table 5.4 will be selected. However, clarification is needed, especially because $CO_2$ is not specifically listed in Table 5.4. We will update this table based on any further information submitted.

FutureGen Response: As discussed above, a comprehensive suite of geochemical and isotopic analyses will be performed on collected fluid samples and analytical results will be used to characterize baseline geochemistry and provide a metric for comparison during operational phases. Selection of this initial analyte list was based on relevance for detecting the presence of fugitive brine and $CO_2$. Results for this comprehensive set of analytes will be evaluated and a determination will be made regarding which analytes to carry forward through the operational phases of the project. This selection process will consider the uniqueness and signature strength of each potential analyte and whether their characteristics provide for a high-value leak-detection capability. Tables 7 and 8 have been updated with the final analyte list, which includes both dissolved gas compositional analysis (including $CO_2$) and measurements of dissolved inorganic carbon and pH.

**Table 14. Sampling Techniques for Target Parameters for the Injection Zone (adapted from Table 5.4 of FutureGen's permit application)**

| Parameter | Volume/Container | Preservation | Holding Time |
|---|---|---|---|
| Major Cations: Al, Ba, Ca, Fe, K, Mg, Mn, Na, Si, | 20-mL plastic vial | Filtered (0.45 µm), $HNO_3$ to pH <2 | 60 days |
| Trace Metals: Sb, As, Cd, Cr, Cu, Pb, Se, Tl | 20-mL plastic vial | Filtered (0.45 µm), $HNO_3$ to pH <2 | 60 days |
| Cyanide (CN-) | 250-mL plastic vial | NaOH to pH > 12, 0.6 g ascorbic acid Cool 4°C, | 14 days |
| Mercury | 250-mL plastic vial | Filtered (0.45 µm), $HNO_3$ to pH <2 | 28 days |
| Anions: $Cl^-$, $Br^-$, $F^-$, $SO_4^{2-}$, $NO_3^-$ | 125-mL plastic vial | Filtered (0.45 µm), Cool 4°C | 45 days |
| Total and Bicarbonate Alkalinity (as $CaCO_3^{2-}$) | 100-mL HDPE | Filtered (0.45 µm), Cool 4°C | 14 days |
| Gravimetric Total Dissolved Solids (TDS) | 250-mL plastic vial | Filtered (0.45 µm), no preservation, Cool 4°C | 7 days |
| Water Density | 100 mL plastic vial | No preservation, Cool 4°C | |
| Total Inorganic Carbon (TIC) | 250-mL plastic vial | $H_2SO_4$ to pH <2, Cool 4°C | 28 days |
| Dissolved Inorganic Carbon (DIC) | 250-mL plastic vial | Filtered (0.45 µm), $H_2SO_4$ to pH <2, Cool 4°C | 28 days |
| Total Organic Carbon (TOC) | 250-mL amber glass | Unfiltered, $H_2SO_4$ to pH <2, Cool 4°C | 28 days |
| Dissolved Organic Carbon (DOC) | 125-mL plastic vial | Filtered (0.45 µm), $H_2SO_4$ to pH <2, Cool 4°C | 28 days |
| Volatile Organic Analysis (VOA) | Bottle set 1: 3-40-mL sterile clear glass vials<br>Bottle set 2: 3-40-mL sterile amber glass vials | Zero headspace, Cool <6 °C, Clear glass vials will be UV-irradiated for additional sterilization | 7 days |
| Methane | Bottle set 1: 3-40-mL sterile clear glass vials<br>Bottle set 2: 3-40 mL sterile amber glass vials | Zero headspace, Cool <6 °C, Clear glass vials (bottle set 1) will be UV-irradiated for additional sterilization | 7 days |
| Stable Carbon Isotopes $^{13/12}C$ ($\delta^{13}C$) of DIC in Water | 60-mL plastic or glass | Filtered (0.45 µm), Cool 4°C | 14 days |
| Radiocarbon $^{14}C$ of DIC in Water | 60-mL plastic or glass | Filtered (0.45µm), Cool 4°C | 14 days |
| Hydrogen and Oxygen Isotopes $^{2/1}H$ ($\delta D$) and $^{18/16}O$ ($\delta^{18}O$) of Water | 60-mL plastic or glass | Filtered (0.45µm), Cool 4°C | 45 days |
| Carbon and Hydrogen Isotopes ($^{14}C$, $^{13/12}C$, $^{2/1}H$) of Dissolved Methane in Water | 1-L dissolved gas bottle or flask | Benzalkonium chloride capsule, Cool 4°C | 90 days |

| Parameter | Volume/Container | Preservation | Holding Time |
|---|---|---|---|
| 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 $C_6$+) | 1-L dissolved gas bottle or flask | Benzalkonium chloride capsule, Cool 4°C | 90 days |
| Radon ($^{222}Rn$) | 1.25-L PETE | Pre-concentrate into 20-mL scintillation cocktail. Maintain groundwater temperature prior to pre-concentration | 1 day |
| pH | Field parameter | None | <1 h |
| Specific Conductance | Field parameter | None | <1 h |

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

**Table 15. Analytical requirements (adapted from Table 5.5 of FutureGen's permit application).**

| Parameter | Analysis Method | Detection Limit or Range | Typical Precision/ Accuracy | QC Requirements |
|---|---|---|---|---|
| Major Cations: Al, Ba, Ca, Fe, K, Mg,<br>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<br>Carbon analyzer, phosphoric acid digestion of TIC | 0.2 mg/L | ±20% | Quadruplicate analyses, daily calibration |
| Dissolved Inorganic Carbon (DIC) | SW846 9060A or equivalent<br>Carbon analyzer, phosphoric acid digestion of DIC | 0.2 mg/L | ±20% | Quadruplicate analyses, daily calibration |
| Total Organic Carbon (TOC) | SW846 9060A or equivalent<br>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<br>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<br>Purge and Trap GC/MS | 0.3 to 15 µg/L | ±20% | Blanks, LCS, spike, spike duplicates per batch of 20 |
| Methane | RSK 175 Mod<br>Headspace GC/FID | 10 µg/L | ±20% | Blanks, LCS, spike, spike duplicates per batch of 20 |
| Stable Carbon Isotopes $^{13/12}C$ ($1^{13}C$) of DIC in Water | Gas Bench for $^{13/12}C$ | 50 ppm of DIC | ±0.2p | Duplicates and working standards at 10% |
| Radiocarbon $^{14}C$ of DIC in Water | AMS for $^{14}C$ | Range: 0 i 200 pMC | ±0.5 pMC | Duplicates and working standards at 10% |

| Parameter | Analysis Method | Detection Limit or Range | Typical Precision/ Accuracy | QC Requirements |
|---|---|---|---|---|
| Hydrogen and Oxygen Isotopes $^{2/1}H$ (δ ) and $^{18/16}O$ ($1^{18}O$) of Water | CRDS $H_2O$ Laser | Range: -500‰ to 200‰ vs. VSMOW | $^{2/1}H$: ±2.0‰<br>$^{18/16}O$: ±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<br>$^{13}C$: ±0.2‰<br>$^{2/1}H$: ±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 compon-ent | 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<br>For indication only | User calibrate, follow manufacturer recommendations |
| Specific Conductance | Electrode | 0 to 100 mS/cm | ±1% of reading<br>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

Laboratory to be used/chain-of-custody procedures:

*[Not specified.]*

FutureGen response: See FutureGen QASP Section B.4 for groundwater and brine sampling, analysis, chain-of-custody procedures.

Quality assurance and surveillance measures:

*[from Section 5.8: Quality Assurance and Surveillance Plan]*

Data QA and surveillance protocols adopted by the project will be designed to facilitate compliance with the requirements specified in 40 CFR 146.90(k).

~~(~~QA~~)~~ requirements for direct measurements within the injection zone, above the confining zone, and within the shallow USDW aquifer that are critical to the MVA program (e.g., pressure and aqueous concentration measurements) are covered in Sections 5.2.2 and 5.2.3 above. QA requirements for selected geophysical methods, which provide indirect measurements of $CO_2$ nature and extent and are being tested for their applicability under site conditions, are not addressed in this plan. These measurements will be performed based on best industry practices and the QA protocols recommended by the geophysical services contractors selected to perform the work.

FutureGen lacks detail in its description of quality assurance and surveillance protocols. FutureGen should provide a more detailed Testing and Monitoring Plan containing this information. [Request from FutureGen.]

FutureGen response: See FutureGen QASP Section B.7 for plume and pressure-front tracking protocols.

Plan for guaranteeing access to all monitoring locations:

*[From the spreadsheet submitted 1/29/14]*

The location of these wells has been finalized, pending final signing of landowner agreements. The land will either be purchased or leased for the life of the project, so access will be secured.

### Indirect Carbon Dioxide Plume and Pressure-~~-~~Front Tracking

FutureGen will conduct indirect plume and pressure-front monitoring to meet the requirements ~~at~~ of 40 CFR 146.90(g)(2). The following information is drawn from Section 5.2.3 of FutureGen's permit application and the additional information submitted in January 2014.

Note: Full evaluation of FutureGen's plume and pressure-front monitoring program will need to take place in conjunction with evaluation of the final AoR modeling submissions. Based on the modeling efforts, FutureGen should provide predicted values over time at each well or monitoring site and describe how the monitoring data will be compared to these results.

FutureGen should also provide details about the planned areal extent/resolution of the geophysical methods. [Request from FutureGen.]

FutureGen response: Preliminary predictions of $CO_2$ saturation over time, based on results from the numerical model used in the UIC permit application, are provided in Figure 6, Figure 7, and Figure 8 for RAT1, RAT2 and RAT3, respectively. RAT locations are provided in Figure 4. Details regarding the areal extent/resolution of the planned geophysical methods are provided in the sections below.

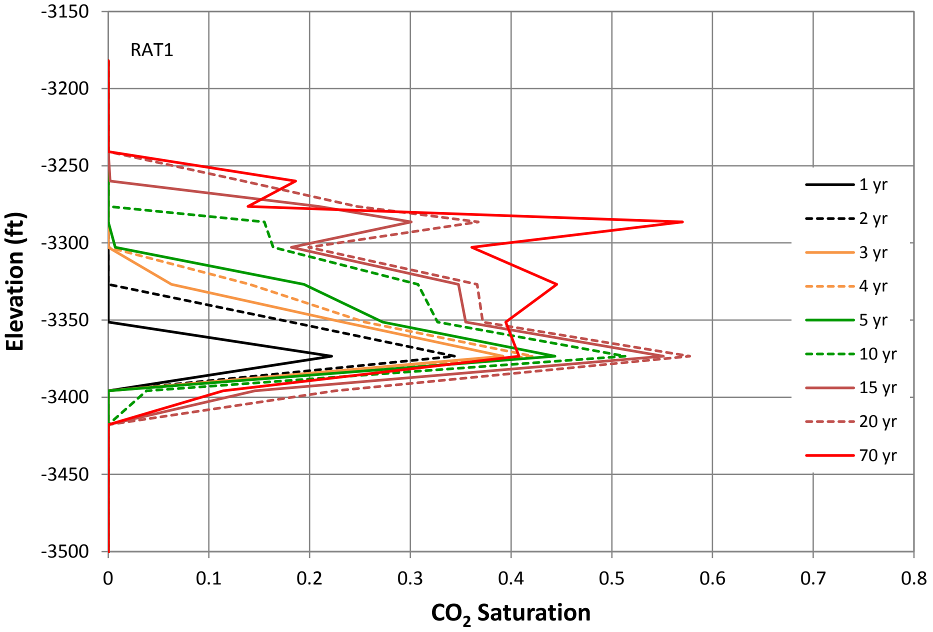

Figure 6. $CO_2$ Saturation Profile for Well Rat1 over Time

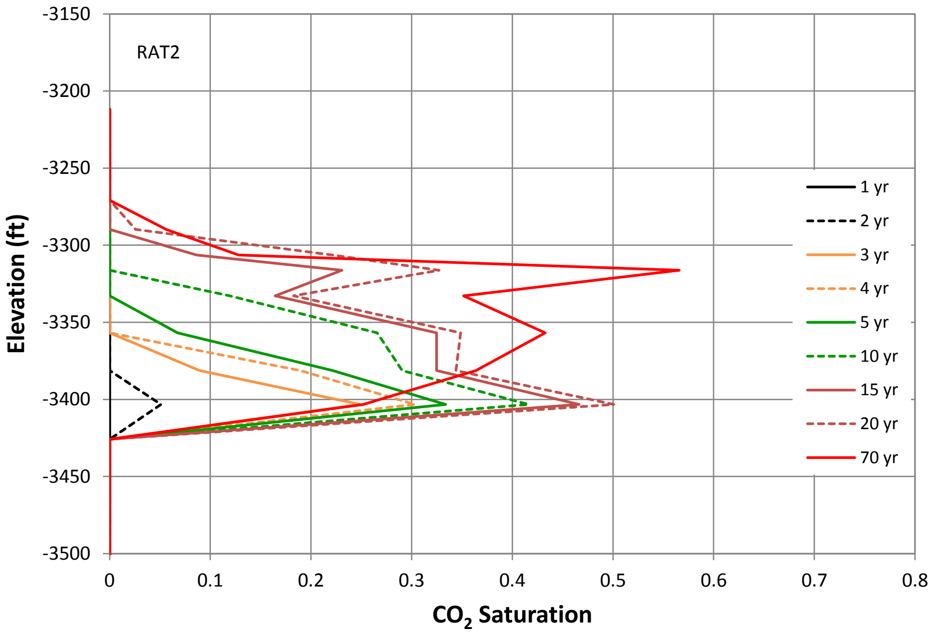

Figure 7. $CO_2$ Saturation Profile for Well Rat2 over Time

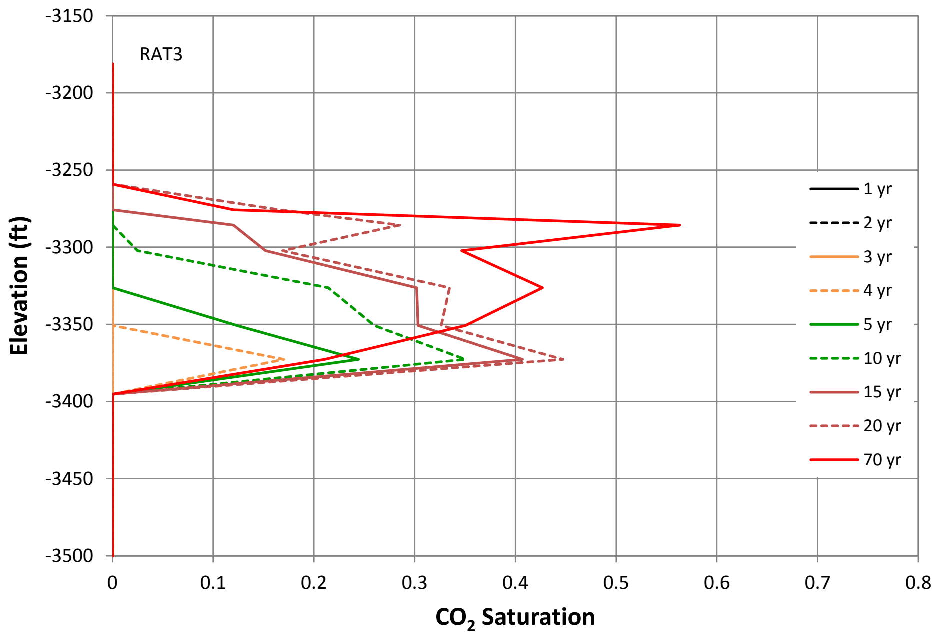

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Figure 8. $CO_2$ Saturation Profile for Well Rat3 over Time

*[From November 2013 response]*

The screening of the indirect monitoring approaches was conducted as part of the Front End Engineering Design process. The selected indirect technologies will include the following:

- ~~pulsed neutron capture~~PNC logging or determination of reservoir $CO_2$ saturation
- integrated deformation monitoring
- time-lapse gravity
- microseismic monitoring.

The monitoring schedule for these ~~monitoring~~ techniques is provided in Table 16.

**Table 16. Monitoring Schedule for Indirect Plume and Pressure-Front Monitoring**

| **Monitoring Technique** | **Location** | **Frequency (Baseline)** | **Frequency (Injection Phase)** |
|---|---|---|---|
| Pulsed~~-~~neutron capture logging | RAT Wells 1 ~~and~~ , 2, and 3 | 3 events | Quarterly for 5 years and annually thereafter |
| Integrated deformation monitoring | 5 locations (see Figure 4 ~~below~~) | 1 year minimum | Continuous |
| Time-lapse gravity monitoring | 46 locations (see Figure 5 ~~below~~) | 3 events | Annually |

| | | | |
|---|---|---|---|
| Passive seismic monitoring (microseismicity) | Surface measurements (see Figure 1 ~~below~~) plus downhole sensor arrays at ACZ Wells 1 and 2 | 1 year minimum | Continuous |

*[Adapted from the spreadsheet submitted 1/29/14] Pulsed-neutron capture logging*

Once the reservoir model has been refined based on site-specific information from the injection site, predictive simulations of $CO_2$ arrival response will be generated for each RAT installation. These predicted responses will be compared with monitoring results throughout the operational phase of the project and significant deviation in observed response would result in further action, including a detailed evaluation of the observed response, calibration/refinement of the numerical model, and possible modification to the monitoring approach and/or storage site operations.

The coordinates (in decimal degrees) of the RAT wells are in Attachment A. Well construction information and well schematics are in Attachment B.

*Integrated deformation monitoring*

Integrated deformation monitoring (see Figure 9 for locations) integrates ground data from permanent Global Positioning System (GPS) stations, tiltmeters, supplemented with annual Differential GPS (DGPS) surveys, and larger-scale Differential Interferometric Synthetic Aperture Radar (DInSAR) surveys to detect and map temporal ground-surface deformation. These data reflect the dynamic geomechanical behavior of the subsurface in response to $CO_2$ injection. These measurements will provide useful information about the evolution and symmetry of the pressure front. These results will be compared with model predictions throughout the operational phase of the project and significant deviation in observed response would result in further action, including a detailed evaluation of the observed response, calibration/refinement of the numerical model, and possible modification to the monitoring approach and/or storage site operations.

Differential Synthetic Aperture Radar (SAR) Interferometry (DInSAR) is a method to generate 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 InSAR 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 per year 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 time-series become larger.

Orbital SAR data will be systematically acquired and processed over the storage site with at least 1 scene per month to obtain advanced InSAR time series. These data will come from X-band TerraSAR-X, C-band Radarsat-2, X-Band Cosmo-Skymed or any other satellite instrument that will be available at the time of data collection.

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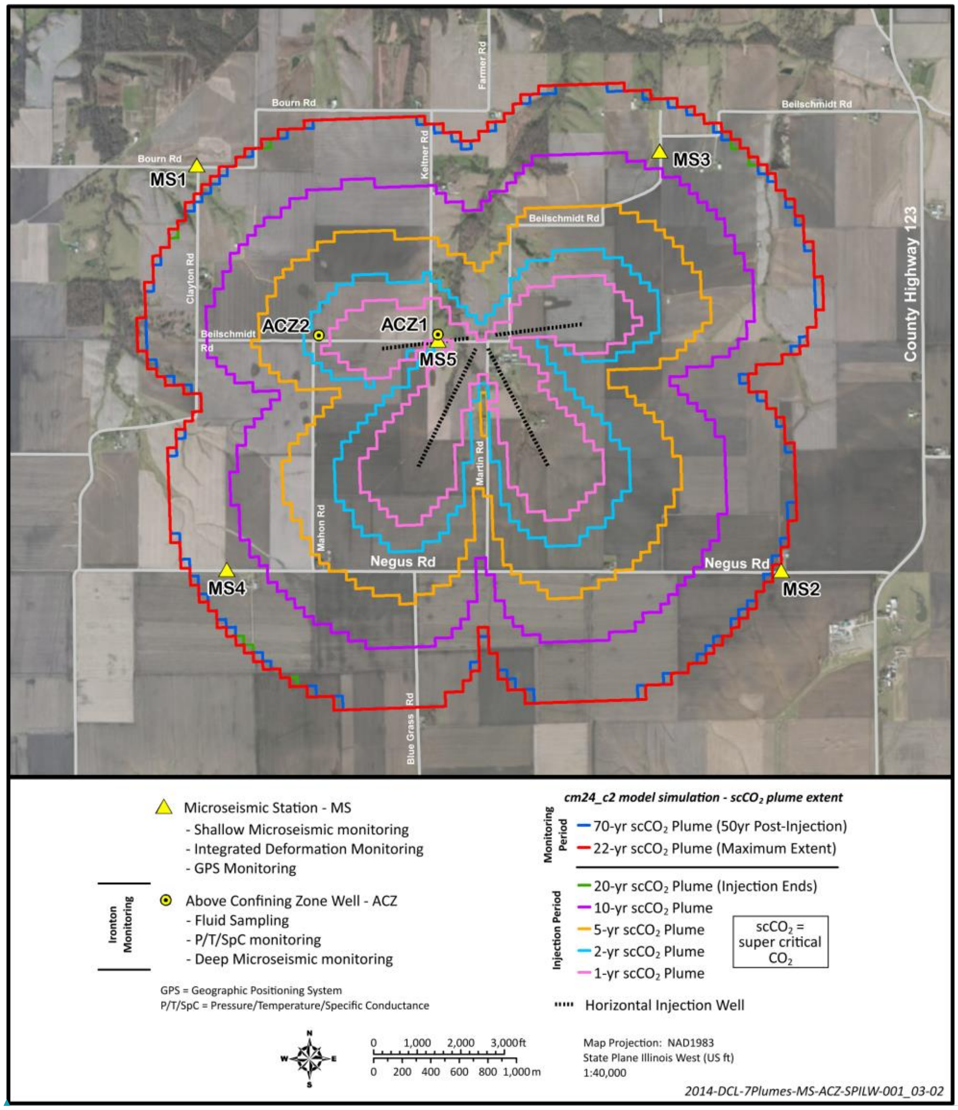

**Figure 9. Microseismic Station and ACZ Well Locations and Predicted Plume Extents at Several Time Intervals**

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 cubes 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 5 permanent tiltmeters and GPS stations will be collected continuously (MS1-MS5 locations in Figure 10). In addition annual geodetic surveys will be conducted using 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 time-lapse gravity monitoring).

To establish a comprehensive geophysical and geomechanical understanding of the FutureGen 2.0 site, InSAR 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.

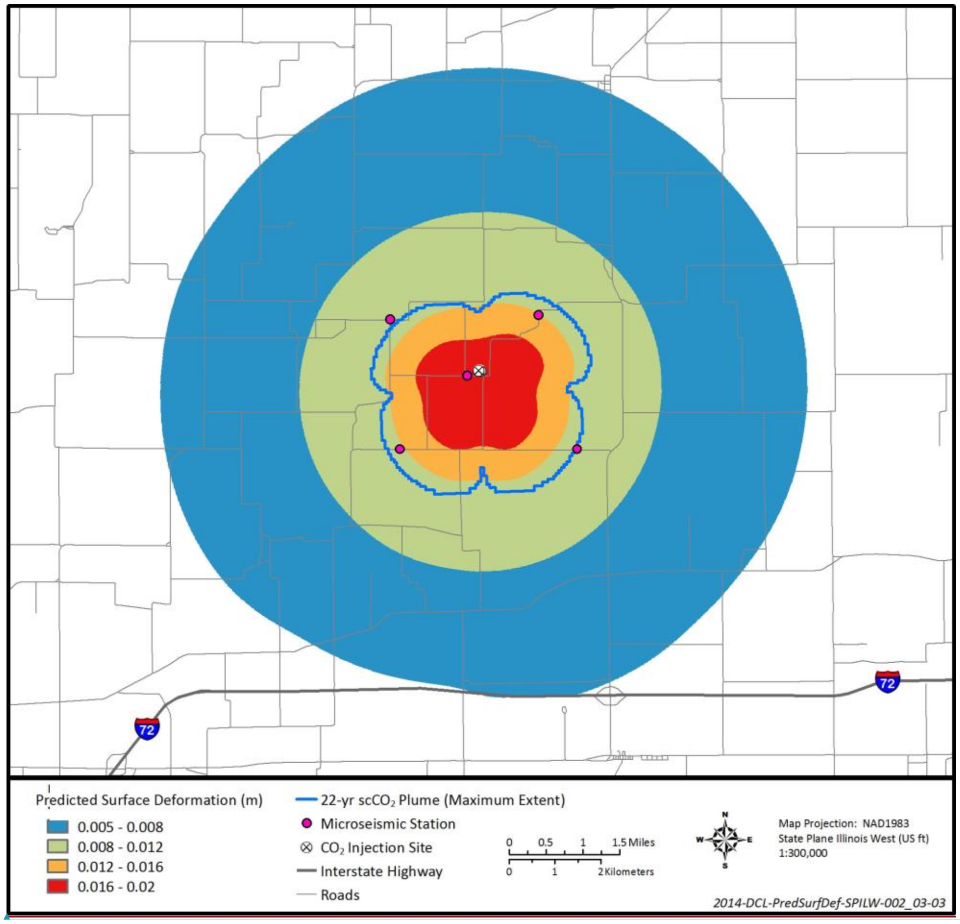

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**Figure 10. Predicted Surface Deformation (in meters) After 20 Years of Injection. Note that 75% of this deformation is reached after 2 years.**

A geomechanical modeling has been performed to evaluate the expected surface deformation associated with the injection of CO2 using the STOMP-CO2/ABAQUS® sequentially coupled simulator. Material properties for the analyses are derived from geophysical well logs and the literature for 31 layers at the FutureGen 2.0 well site. The median values of Young’s modulus and the Poisson ratio are taken from geophysical well logs. STOMP-CO2 was used to model the flow and transport of $CO_2$ for the 20 year injection period, assuming injection of 1.1 MMT of $CO_2$ per year. The information from STOMP-CO2 is passed to ABAQUS at each selected time step, and an ABAQUS 3-D finite element model calculated the strains, stresses (including thermal stresses), and fluid pressure; updated the permeability and porosity; and evaluated a fracture criterion. The resulting surface uplift after 20 years of injection is presented in Figure 10. Considering the level of precision of the methodology (see above) a conservative threshold of detection of 5 mm has been chosen which corresponds roughly to 180 Psi pressure increase at reservoir depth. The maximum deformation of 20 mm is reached close to the injection well where the maximum pressure increase is observed. These values for surface deformations are within the detection range of the integrated deformation network as designed.

~~**Figure 4. Collocated Microseismic and Integrated Surface Deformation Monitoring Stations.**~~

~~Locations for the microseismic stations must be identified with Lat/Long coordinates.  These  coordinates can be tabulated and attached to the end of the testing and monitoring plan template.~~

### *Time-lapse gravity monitoring*

The objective of gravity monitoring is to observe changes in density distribution in the subsurface~~,~~ caused by the migration of fluids, which could potentially help~~. I could~~ and; ~~to help~~ define ~~estimate~~ the areal extent of the $CO_2$ plume or detect leakage (Figure 11). This technology has been successfully applied to a variety of subsurface injection studies, including carbon sequestration at Sleipner (Arts et al. 2008); aquifer recharge studies in Utah and elsewhere (Chapman et al. 2008; Davis and Batzle 2008); and to hydrocarbon waterflood surveillance in Alaska (Ferguson et al. 2007).

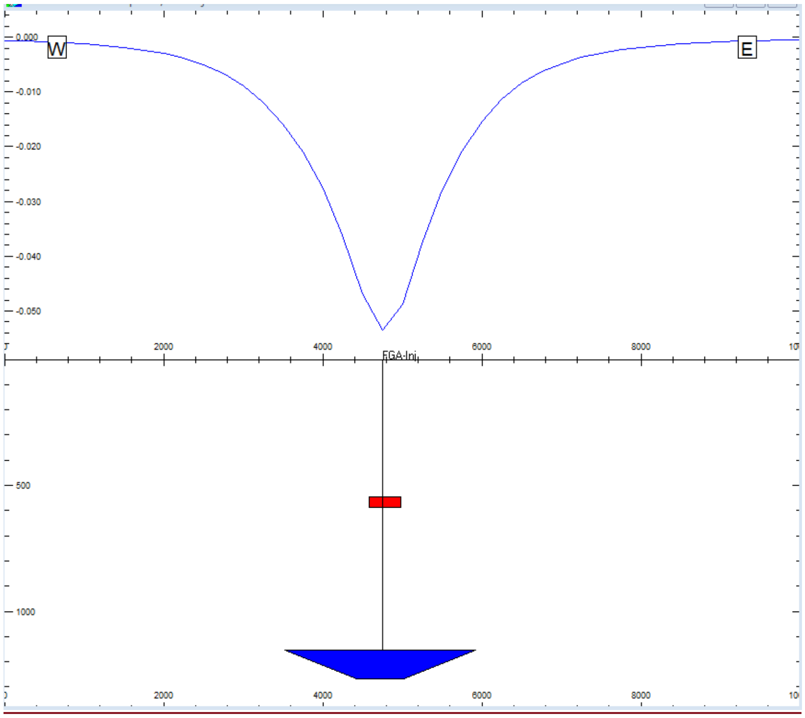
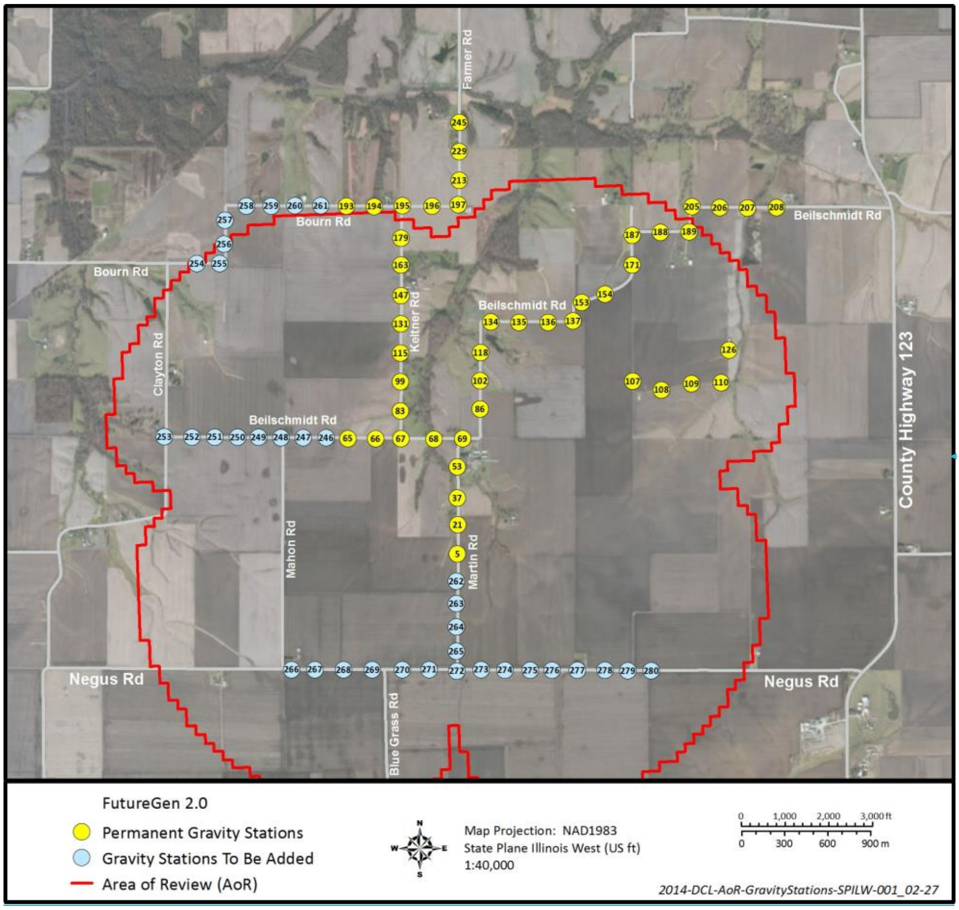


**Figure 11. Theoretical Case of Gravity Anomaly Caused by the 20-Year $CO^2$ Plume (Blue Body) and by a 1% Leak at the 500-m Depth (Red Body). The leak decreases by 25 microgal, the signal due to the plume alone.**

Considering the depth of the reservoir, gravity changes at the surface are expected to be small, close to the detection limit of 10 microGal, but analysis of long-term trends may allow for tracking of the $CO_2$ plume. The cost of implementing this technology is the lowest of all methods considered and is combined with DGPS surveys conducted as part of the integrated surface deformation monitoring. Time-lapse gravity monitoring is done using repetitive annual surveys at a series of points located at the ground surface (permanent stations). Changes of gravity anomaly with time is 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 solution, this monitoring method could rarely be used alone and gives the best results in complement of other methods (deformation, microseismic).

Forty six permanent stations were established in 2011 during a gravity survey for the purpose of future reoccupation surveys. Approximately 35 complementary stations will be established for a total of 81 stations. A map of the gravity stations is provided in Figure 12. No trigger levels will be defined. The coordinates (in decimal degrees) of the stations are provided in Attachment D.

~~The coordinates of these stations are provided in attachment F.~~



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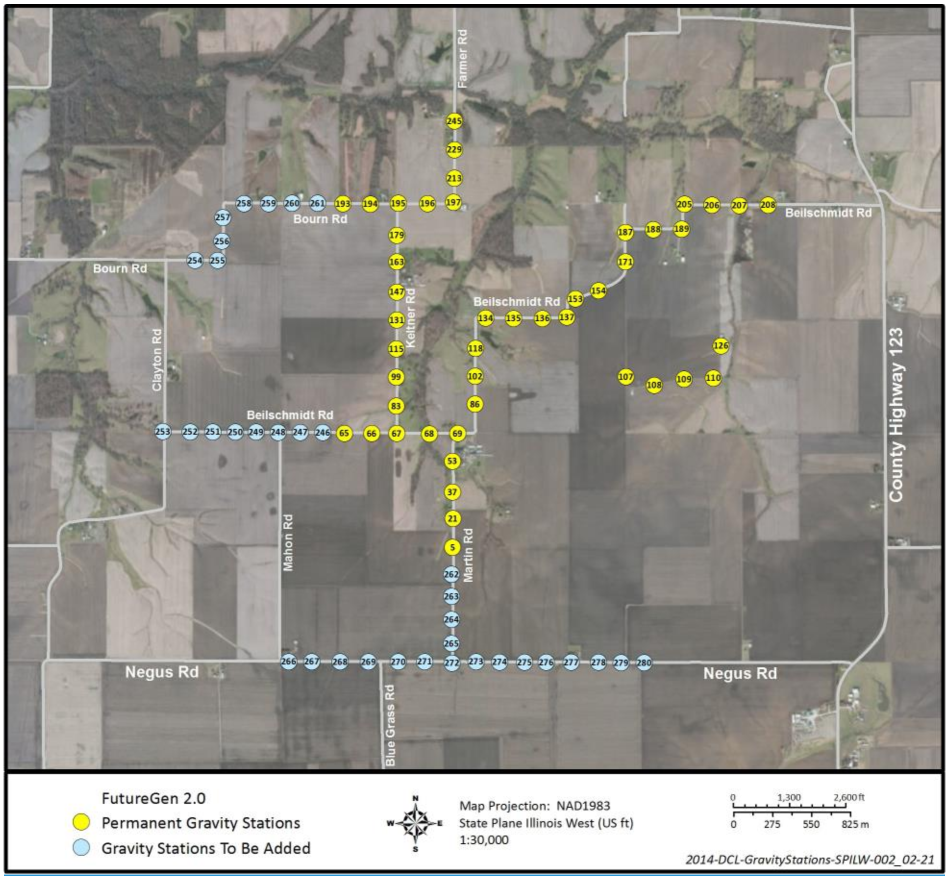

**Figure 12.** **Location of Permanent Gravity Stations (with supplemental DGPS)**

~~Locations for the permanent gravity stations must be identified with Lat/Long coordinates. These coordinates can be tabulated and attached to the end of the testing and monitoring plan template.~~

*Passive seismic monitoring (microseismicity)*

Note: Some of this information may need to be included in the Emergency and Remedial Response Plan instead of or in addition to this Testing and Monitoring Plan.

FutureGen response: Seismic monitoring considerations are also covered in the Emergency and Remedial Response Plan.

The objective of the microseismic monitoring network (~~Figure 4~~Figure 9; downhole arrays will also be installed at the two ACZ wells) 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

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from the distribution of seismic events, and 3) identifying features that may indicate areas of caprock failure and possible containment loss. Once a seismic event has been identified, a decision must be made regarding the level of impact a given event could have on storage site operations, whether a response is required, and if yes, what the response will be.

This decision and response framework will consist of an automated event location and magnitude determination, followed by an alert for a technical review in order to reduce the likelihood of false positives. Identification of events with sufficient magnitude or that are located in a sensitive area (caprock) will be used as input for decisions that guide the adaptive strategy. Seismic events that affect the operations of $CO_2$ injection can be divided into two groups/tiers: 1) events that create felt seismicity at the surface and may lead to public concern or structural damage, and 2) events not included in group one, but that might indicate failure or impending failure of the caprock. The operational protocol for responding to events in group one (Tier I) will follow a "traffic light" approach (modified after Zoback 2012; National Research Council 2012) that uses three operational states:

1. Green: Continue normal operations unless injection-related seismicity is observed with magnitudes greater than M = 2.

2. Yellow: Injection-related seismic events are observed with magnitude 2 < M< 4. The injection rate will be slowed and the relationship between rate and seismicity will be studied to guide mitigation procedures, including reduced operational flow rates.

3. Red: Magnitude 4 or greater seismic events are observed. Injection operations will stop and an evaluation will be performed to determine the source and cause of the ground motion.

Tier II operational responses to an event or collection of events that indicate possible failure of the primary confining zone may include initiation of supplemental adaptive monitoring activities, injection rate reduction in one or more injection laterals, or pressure reduction using brine extraction wells.

## Areal Extent and Resolution

Parameter resolution tests can also be done using a grid search method by generating synthetic observed data from calculated travel times to which a specified amount of noise is added (Eisner et al. 2009EPA 1998

). The chi squared statistic can be used to determine whether a given trial solution is within a certain percentile confidence interval of the true value. The chi squared statistic can be calculated from the trial, $d^{trial}$, observed data, $d^{obs}$, and standard deviation, σ, for each station using the following formula:

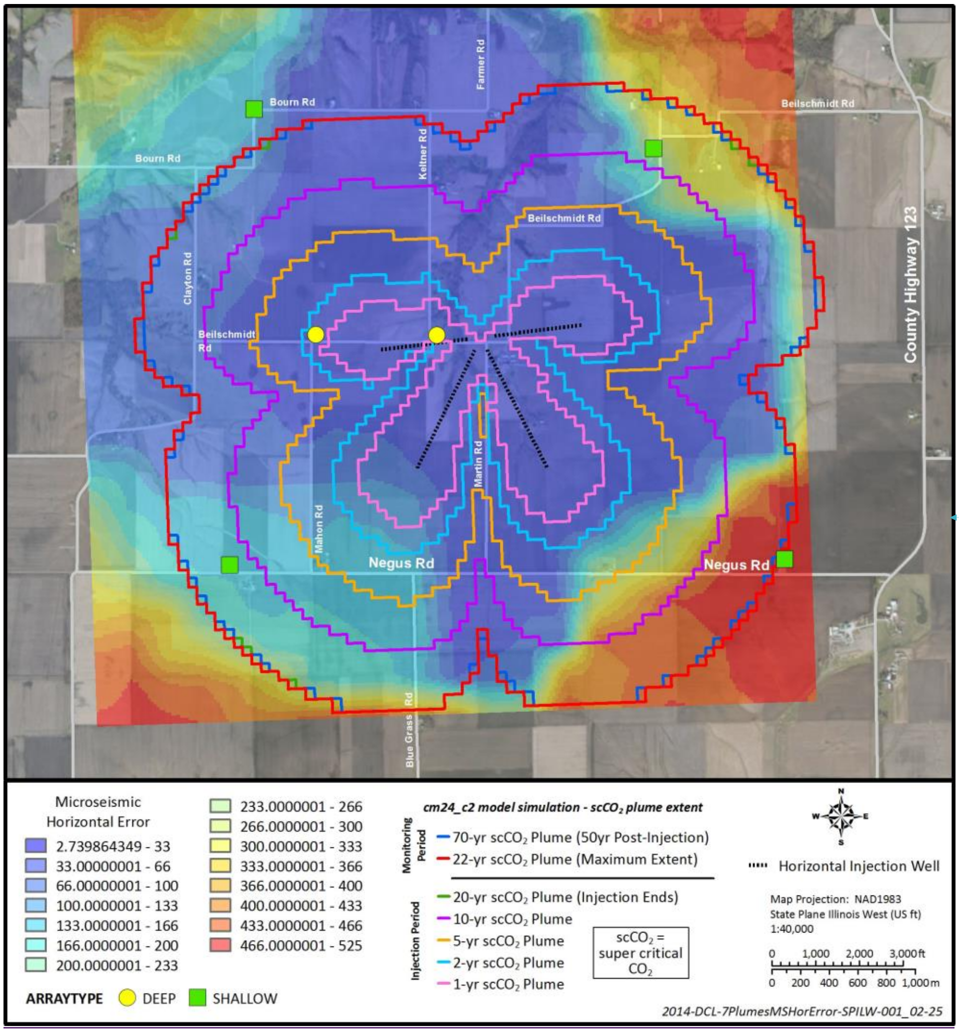
$$\chi^2 = \sum \frac{(d_i^{trial} - d_i^{obs})}{\sigma_i} \qquad (1)$$

Field Code Changed

If the chi squared value is less than the cumulative chi squared statistic for the specified percentile and degree of freedom then the trial solution is included in the set of solutions that lie within the confidence range. If this process is repeated for a large number of trial events the size of the confidence interval for each of the parameters can be estimated. To examine the performance of a number of possible network geometries that might be used for microseismic monitoring at the FutureGen $CO_2$ storage site a grid search based uncertainty analysis was performed. For this test a homogeneous velocity model was used to speed the required calculations. The velocity used was determined from an arithmetic average of the velocity log from the characterization borehole and the standard deviation of the travel time errors was set at 1 ms.

Assuming that there are no errors in the velocity model, two primary parameters affect the location errors of a given seismic sensor network: sensor geometry and the maximum observable event distance. A number of cases were investigated using various network geometries and maximum event distances; results for the selected microseismic network design are presented below. Location uncertainty can be divided into horizontal (northing and easting) and vertical (depth) uncertainties (shown in Figure 13 and Figure 14, respectively).

**Commented [DA1]:** Updated version of the uncertainty maps provided to on 3/5/2014.



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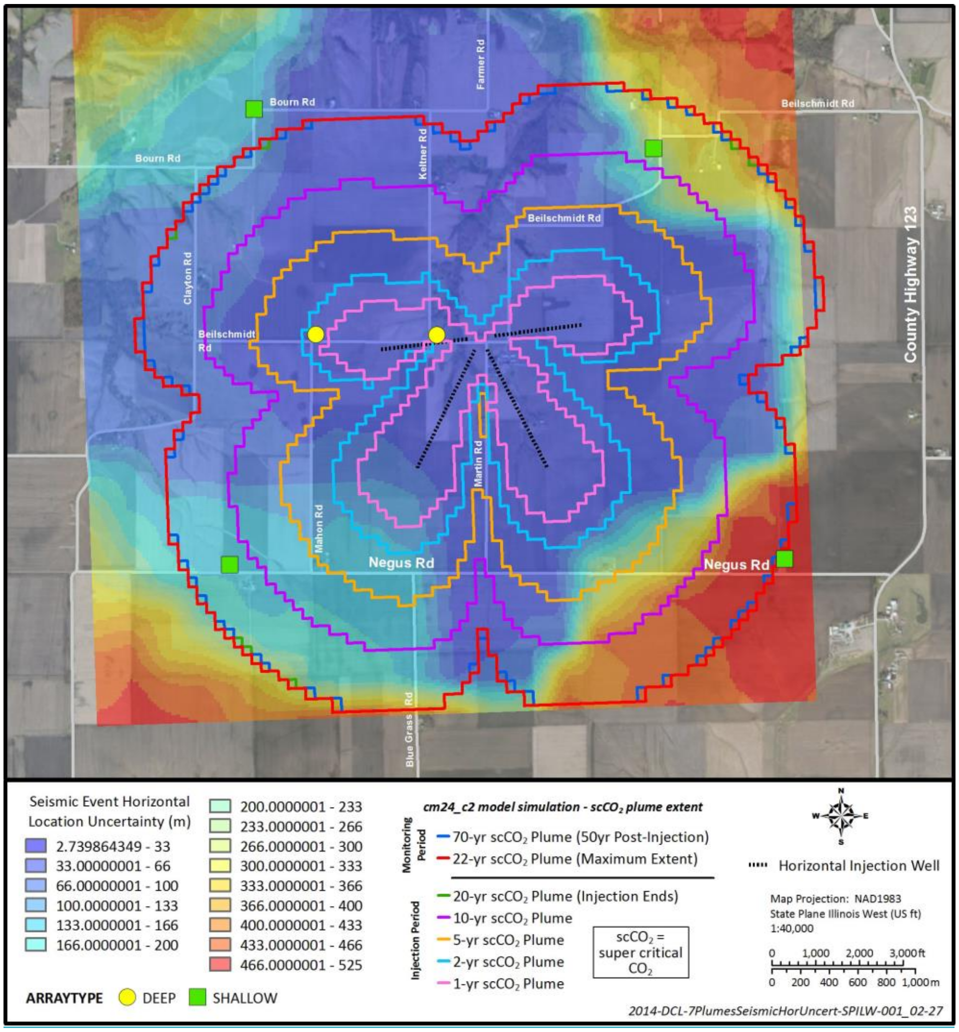
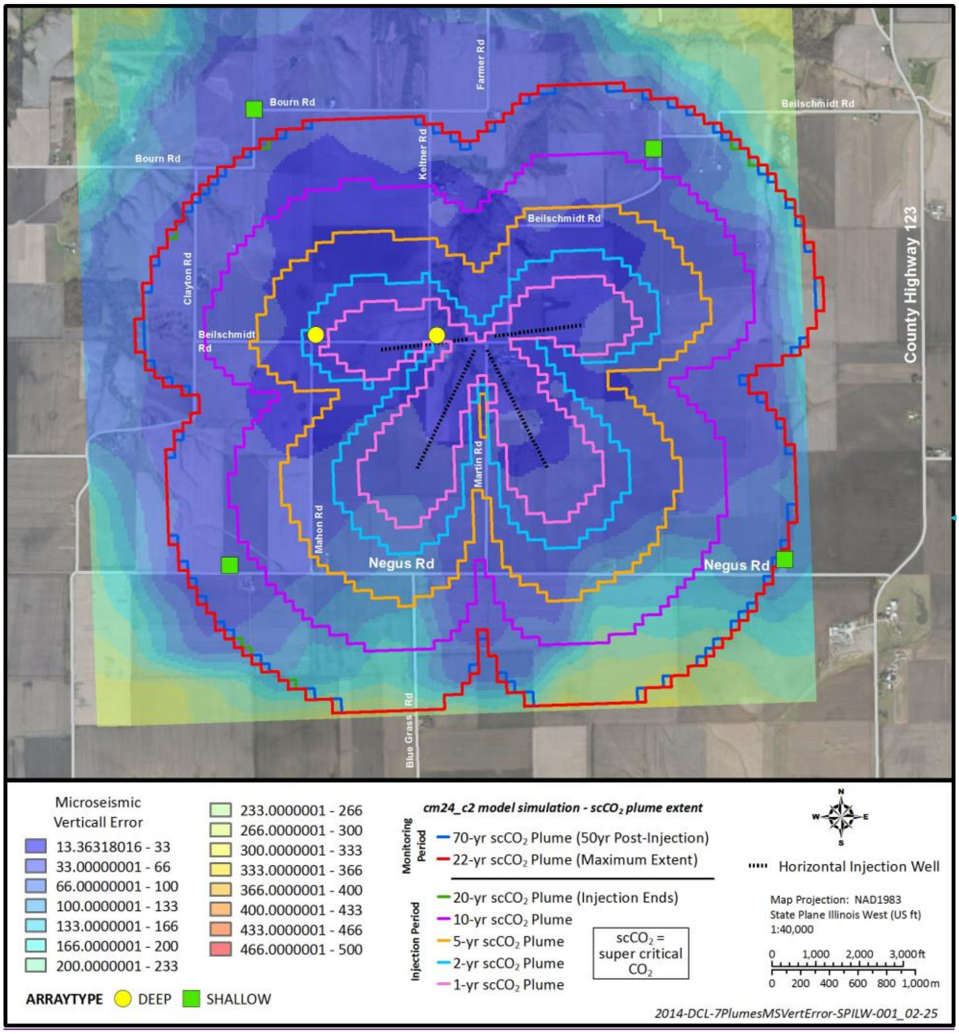


Figure 13. Seismic Event Horizontal Location Uncertainty in Meters



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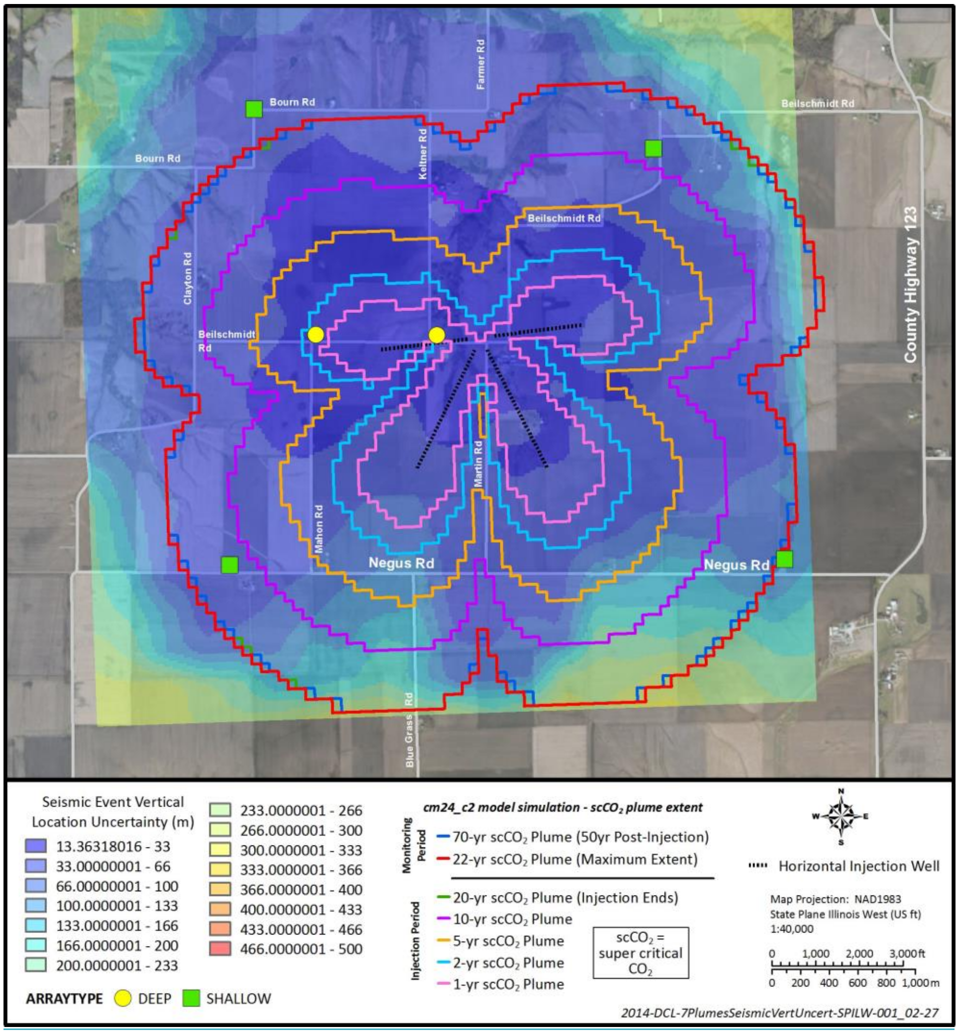

Figure 14. Seismic Event Vertical Location Uncertainty in Meters

The UIC Program Director will not require monitoring under 146.90(h). The paragraphs and Table 17, identified under "Surface Air and/or Soil-Gas Monitoring," can be deleted.

## Surface Air and/or Soil-Gas Monitoring (if required by the UIC Program Director)

Future Gen is considering certain activities for surface air/and soil-gas monitoring, as well as other types of monitoring, which are described in Section 5. It is not known at this time if the EPA will require this type of monitoring.

This section may be deleted or revised, pending Region 5's decision to require surface air/and soil-gas monitoring. (Note: They aren't planning on doing surface monitoring unless there is a leak or EPA requires it. If it's the former, this may belong in the Emergency and Remedial Response Plan, if not already there.)

FutureGen response: Baseline data will be collected but FutureGen is not planning to continue these activities throughout operational phases of the project unless warranted. The UIC Program Director has indicated that this section will not be included in the permit.

*[From Section 5.0: Testing and Monitoring Plan]*

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

Sampling methods: *[Not planned unless required.]*

Analytical techniques: *[Potential methods in table below.]*

**Table 17. Potential Techniques for Near-Surface-Monitoring (from Table 5.2 of FutureGen's permit application)**

| Monitoring Category | Monitoring Method | Description |
|---|---|---|
| Soil-Gas Monitoring | Shallow soil-gas monitoring | Soil-gas collector chambers and/or standard soil-gas sampling points will be used to monitor the concentration of $CO_2$ and other non-condensable gases (e.g., N, O) in shallow soils. |
| | Tracer and isotopic signature monitoring | Soil-gas sampling for carbon and oxygen isotopic signature and/or tracer compounds injected along with the $CO_2$ to improve leak-detection |

| | | |
|---|---|---|
| | | capabilities. |
| Atmospheric Monitoring | Fixed-point $CO_2$ and tracer monitoring | Continuous $CO_2$ measurement at fixed location, with routine sampling for $CO_2$ and tracer gas concentrations. Tracer gases will provide improved leak-detection capability. |
| | Mobile $CO_2$ and tracer monitoring | Periodic measurements of $CO_2$ and tracer gas using a mobile, real-time instrument, near injection/monitoring wells and along transects spanning the AoR. |
| | Weather station (at two fixed-point locations | Measurements of air temperature, relative humidity, precipitation, barometric pressure, solar radiation, soil moisture, and soil temperature. |
| Ecological Monitoring | Baseline ecological survey | Pre-operational monitoring and characterization to establish baseline conditions for comparisons with operational monitoring results. |
| | Continuous surface-water monitoring | Continuous measurement of pH, temperature, electrical conductivity, and dissolved oxygen content of nearby surface waters. |
| | Remotely sensed data for vegetation condition assessment | Satellite imagery used to characterize vegetation conditions and detect subtle changes in normal plant growth processes and relative vegetation stress. |

Laboratory to be used/chain-of-custody procedures: *[Not planned unless required.]*

Quality assurance and surveillance measures: *[Not planned unless required.]*

Plan for guaranteeing access to all monitoring locations: *[Not planned unless required.]*

## Additional Monitoring (if required by the UIC Program Director)

Future Gen is considering additional monitoring, which is described in Section 5 of the permit application and presented in the Surface Air and/or Soil-Gas Monitoring section of this checklist above. It is not known at this time if the EPA will require additional monitoring.

## Attachments

Map showing monitoring well locations; boundary of geophysical survey areas Monitoring well schematics

**Commented [DA2]:** Boundary for microseismic already in the text (see maps with horizontal/vertical error)

**References** (starter list)

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

Arts et al. 2008

ASTM 2011

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Eisner L., Heigl W., Duncan P. and W. Keller, 2009, Uncertainties in passive seismic monitoring: The Leading Edge, 28, 648– 655.

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Zoback, M.D., 2012, Managing the seismic risk posed by waste water disposal. Earth Magazine, 57, 38-43. CONFIRMED

National Research Council. *Induced Seismicity Potential in Energy Technologies* . Washington, DC: The National Academies Press, 2013. CONFIRMED

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# Attachment A

## Coordinate Locations of the Deep Monitoring Wells

| Well ID | Well Type | Latitude (WGS84) | Longitude (WGS84) |
|---|---|---|---|
| **ACZ1** | Above Confining Zone 1 | 39.80034315 | -90.07829648 |
| **ACZ2** | Above Confining Zone 2 | 39.80029543 | -90.08801028 |
| **USDW1** | Underground Source of Drinking Water | 39.80048042 | -90.0782963 |
| **SLR1** | Single-Level in-Reservoir 1 | 39.8004327 | -90.08801013 |
| **SLR2** | Single-Level in-Reservoir 2 | 39.80680878 | -90.05298062 |
| **RAT1** | Reservoir Access Tube 1 | 39.80035565 | -90.08627478 |
| **RAT2** | Reservoir Access Tube 2 | 39.78696855 | -90.06902677 |
| **RAT3** | Reservoir Access Tube 3 | 39.79229199 | -90.08901656 |

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# Attachment B

## Monitoring Well Construction and Schematics

- ACZ Well Construction and Drilling Information
- USDW Well Construction and Drilling Information
- SLR1 Well Construction and Drilling Information
- SLR2 Well Construction and Drilling Information
- RAT Well Construction and Drilling Information

## ACZ Well Construction and Drilling Information

Construction detail for the Above Confining Zone (ACZ) wells is provided in Figure B-1. One of the ACZ wells will be located approximately 1,000 ft west of the injection well site, within the region of highest pressure buildup. The other ACZ well will be located approximately 0.75 mi west of the injection site on the same drill pad as single-level in-reservoir well 1 (SLR1). These selected ACZ locations focus early-detection monitoring within the region of elevated pressure and are proximal to six of nine project-related caprock penetrations (four injection wells, two reservoir wells, and three reservoir access tubes [RATs]). The ACZ wells will be used to collect fluid samples, for continuous pressure, temperature, specific conductance (P/T/SpC) and microseismic monitoring. A fiber-optic cable with integral geophones for microseismic monitoring will be secured to the outside of the casing and cemented in place. This design will permit unobstructed access to the inside of the casing and screen for planned sampling and monitoring activities.

To begin, a 30-in. borehole will be drilled and 24-in.-OD conductor casing will be installed to near the contact with Pennsylvanian bedrock (150 ft) (Figure B-1). Next, the boring will step down to a 20-in. borehole and 16-in. casing to approximately 600 ft. Below 600 ft, the hole will step down to a 14-3/4-in. hole lined with 10-3/4-in. casing to below the base of the Potosi Dolomite. Casing to the base of the Potosi Dolomite (~3,100 ft) is needed to case off the karstic lost-circulation zone encountered while drilling the stratigraphic well. After cementing the 10-3/4-in. casing in place a 9-1/2-in. borehole will be drilled into the top of the underlying confining zone. The base of the Ironton Sandstone in the stratigraphic well was 3,425 ft bgs. The bottom of the ACZ wells should be drilled a bit further (to ~3,470-ft depth) into the top of the Eau Claire Formation to positively identify the Ironton/Eau Claire contact and to create sufficient borehole to accommodate a 50-ft-long section of blank 5-1/2-in. casing below the well screen. If the ongoing modeling effort focused on evaluating early-detection capabilities in the ACZ wells indicates that detection is improved by moving the screen to near the top of the Ironton Formation, then the borehole will be plugged back prior to well completion.

**Commented [DA3]:** probably not needed.

**Vince:** I don't see any problem mentioning it, I say we keep it.

After the 9-1/2-in. borehole has been drilled to total depth, the borehole will be developed to remove mud cake, cuttings, and drill fluids via circulation. Development will continue until all drilling mud has been effectively removed from the borehole wall. After the borehole has been circulated clean, a final casing string will be installed. The final casing string will be 5-1/2-in. OD and will include a ~20-ft-long stainless-steel well screen installed across the selected monitoring interval. A 50-ft-long section of blank casing will be attached below the screen to provide a sump for collecting any debris that may enter the well over time. A swellable packer may be placed immediately above and below the screened interval to help ensure zonal isolation (see Figure B-2). The annulus casing packer (ACP) and a stage-cement tool will be placed above the well screen to isolate and keep cement away from the screen. In addition to the stainless-steel well screen, the lowermost 200 ft of the 5-1/2-in. casing string (including the section that spans the Ironton Sandstone [3,286−3,425 ft bgs]) will be a corrosion-resistant alloy material (e.g., S13Cr110). The remainder of the 5-1/2-in. casing string will be carbon steel. Corrosion-resistant cement will be used to cement the final casing string up to ~3,100-ft depth. Regular cement will be used to seal the remainder of the 5-1/2-in. casing to ground surface. All other casing strings will be cemented with standard well cement. A summary of the borehole and casing program for the ACZ wells is in

Table B.1.

**Table B.1. Casing and Borehole Program for the ACZ Monitoring Wells**

| Section | Borehole Depth (ft) | Borehole Diam. (in.) | Casing OD (in.) | Casing Grade | Casing weight (lb/ft) | Casing Connection |
|---|---|---|---|---|---|---|
| Conductor Casing | 150 | 30 (min.) | 24 | B | 140 | PEB |
| Surface Casing | 600 | 20 | 16 | K-55 | 84 | BTC |
| Intermediate Casing | 3,100 | 14-3/4 | 10-3/4 | K-55 | 51 | BTC |
| Long Casing (with a 20-ft-long screened section) | 3,470 | 9-1/2 | 5-1/2 | J-55 (0-3,100 ft);<br>S13Cr110 (3,100−3,470 ft) | 17 | LTC (J-55); Vam Top or similar (S13Cr110) |

Grade B is equivalent to line pipe; BTC = buttress thread connection; Cr = chromium; LTC = long thread connection; PEB = plain end beveled.

Notes:

Actual casing grades and weights may differ based on material available at the time of construction.

All depths are approximate and may be adjusted based on information obtained when the well is drilled.

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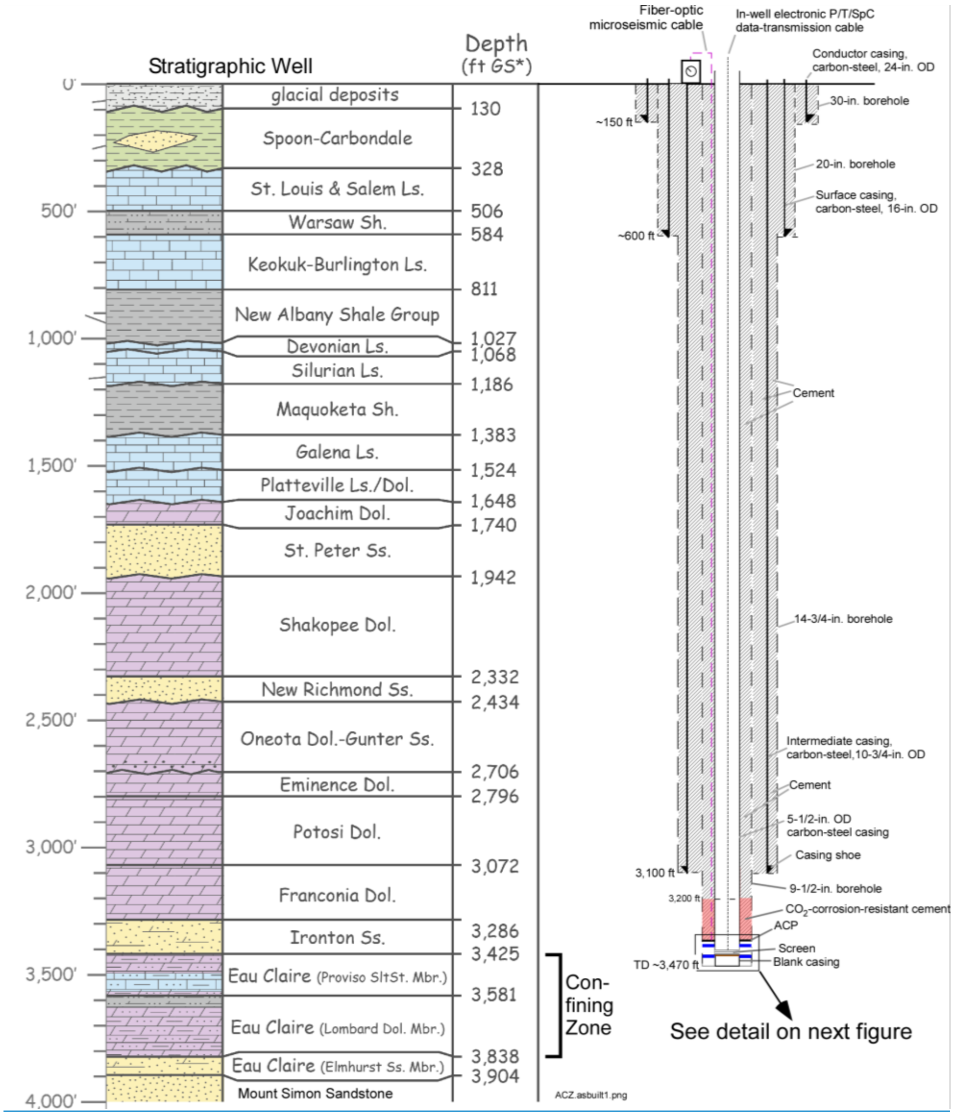

Figure B-1. Well Construction Diagram for the ACZ Monitoring Wells

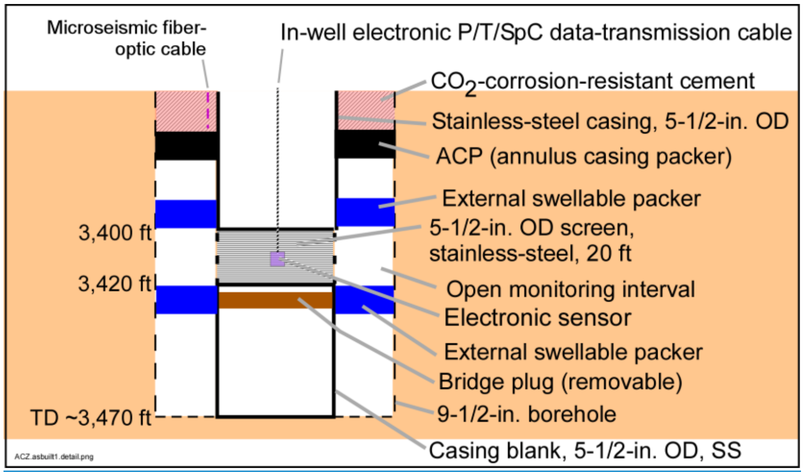

Figure B-2. Construction Detail for ACZ Monitoring Wells

## USDW Well Construction and Drilling Information

A single monitoring well (USDW1) will be installed in the Ordovician St. Peter Sandstone, the lowermost underground sources of drinking water (USDW) above the FutureGen injection reservoir. The St. Peter Sandstone is considered the lowermost USDW, because the measured total dissolved solids (TDS) content from this unit at the FutureGen stratigraphic well was 3,700 mg/L, which is below the regulatory limit of 10,000 mg/L for designation as a potential USDW. A single regulatory compliance well will be installed within this lowermost USDW aquifer, on the same drill pad with the ACZ1 early-detection monitoring well, which is within the region of highest pressure buildup.

The USDW1 well will be a 5-1/2-in.-OD well with a 20-ft-long, stainless-steel screen section placed across the monitoring interval (estimated at 1,930 to 1,950 ft). An evaluation of monitoring requirements for this well indicates that a 5-1/2-in.-OD casing string will be sufficient to meet project objectives (i.e., allow access for fluid sampling and installation of downhole P/T/SpC probes. The current plan calls for free hanging the P/T/SpC probes by wireline within the 5-1/2-in. casing; however, the design may be revised to include tubing and packer to secure the probe. A well schematic is shown in Figure B-3.

To begin, a 20-in. borehole will be drilled and 16-in. conductor casing will be installed to near the contact with Pennsylvanian bedrock (Figure B-3). Next, the boring will step down to a 14-3/4-in. borehole and 10-3/4-in. casing to approximately 600 ft. After cementing the 10-3/4-in. casing in place, a 9-1/2-in. borehole will be drilled to a short distance below the base of the USDW (St. Peter Sandstone) (to ~2,000-ft depth) to positively identify the St. Peter Sandstone/Shakopee Dolomite contact. After the 9-1/2-in. borehole has been drilled to total depth, the borehole will be developed to remove mud cake, cuttings, and drill fluids via circulation. Development will continue until all drilling mud has been effectively removed from the borehole wall. After the borehole has been circulated clean, a final casing string will be installed. The final casing string will be 5-1/2-in. OD and will include a ~20-ft-long stainless-steel well screen near the bottom (see screened interval construction detail for USDW1 in Figure B-4).

Stainless-steel casing (e.g., 13Cr), 5-1/2-in. OD, will be used in the lower 300 ft of the well including the entire St. Peter Sandstone. Standard carbon-steel casing will be used above depths of ~1,700 ft. A 20-ft-long, 5-1/2-in.-OD stainless-steel well screen will be incorporated into the final casing string and positioned to span the desired monitoring interval. Approximately 50 ft of blank casing will extend from immediately below the screen to the bottom of the well (Figure B-3). External swellable packers may be placed above and below the screened interval to help ensure zonal isolation (see Figure B-4). A removable bridge plug may be installed just below the screen to isolate it from the rat hole below. Standard well cement will be used to cement all casing strings.

A summary of the borehole and casing program for the USDW1 well is provided in Table B-2.

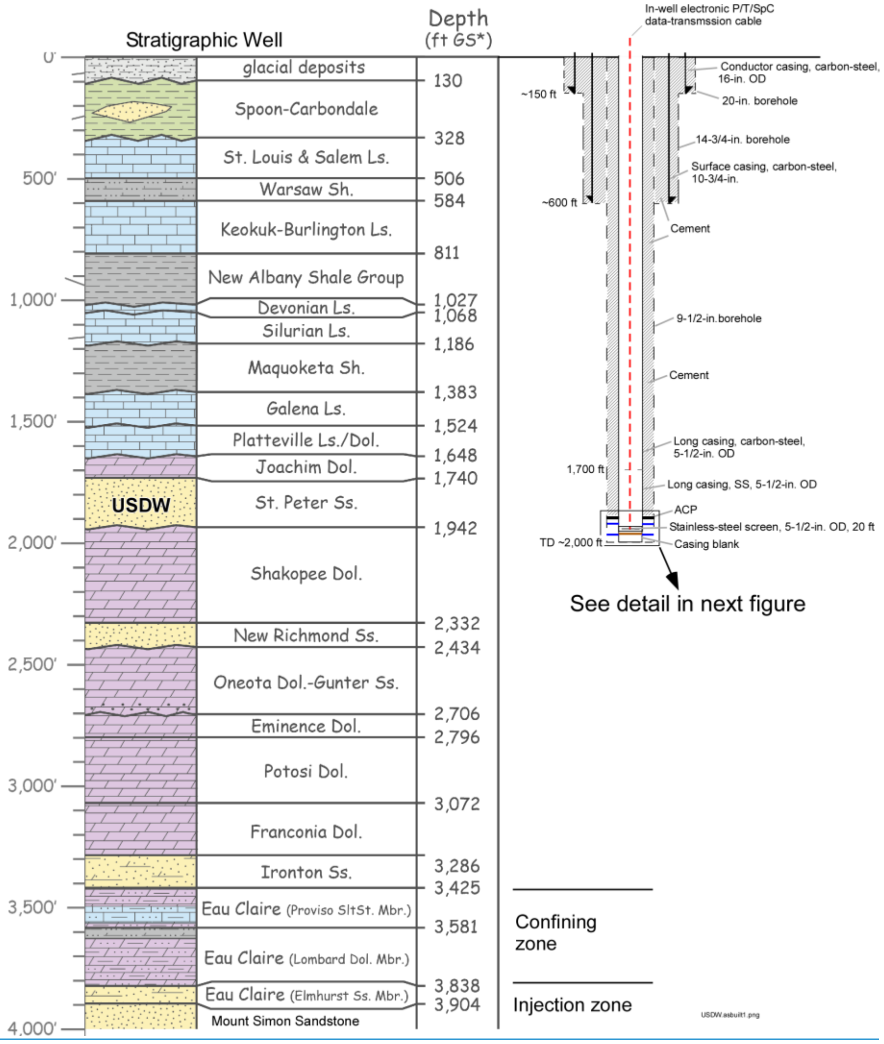

Figure B-3. Well-Construction Diagram for the USDW1 Monitoring Well

~~To begin, a 20-in. borehole will be drilled and 16-in. conductor casing will be installed to near the contact with Pennsylvanian bedrock (Figure 10.9). Next, the boring will step down to a 14-3/4-in. borehole and 10-3/4-in. casing to approximately 600 ft. After cementing the 10-3/4-in. casing in place, a 9-1/2-in. borehole will be drilled to a short distance below the base of the USDW (St. Peter Sandstone) (to ~2,000-ft depth) to positively identify the St. Peter Sandstone/Shakopee Dolomite contact. After the 9-1/2-in. borehole has been drilled to total depth, the borehole will be developed to remove mud cake, cuttings, and drill fluids via circulation. Development will continue until all drilling mud has been effectively removed from the borehole wall. After the borehole has been circulated clean, a final casing string will be installed. The final casing string will be 5-1/2-in. OD and will include a ~20-ft-long stainless-steel well screen near the bottom (see screened interval construction detail for USDW1 in Figure 4).~~

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~~Stainless-steel casing (e.g., 13Cr), 5-1/2-in. OD, will be used in the lower 300 ft of the well including the entire St. Peter Sandstone. Standard carbon-steel casing will be used above depths of ~1,700 ft. A 20-ft-long, 5-1/2-in.-OD stainless-steel well screen will be incorporated into the final casing string and positioned to span the desired monitoring interval. Approximately 50 ft of blank casing will extend from immediately below the screen to the bottom of the well (Figure 3). External swellable packers may be placed above and below the screened interval to help ensure zonal isolation (see Figure 4). A removable bridge plug may be installed just below the screen to isolate it from the rat hole below. Standard well cement will be used to cement all casing strings. A summary of the borehole and casing program for the USDW well is provided in Table 2.~~

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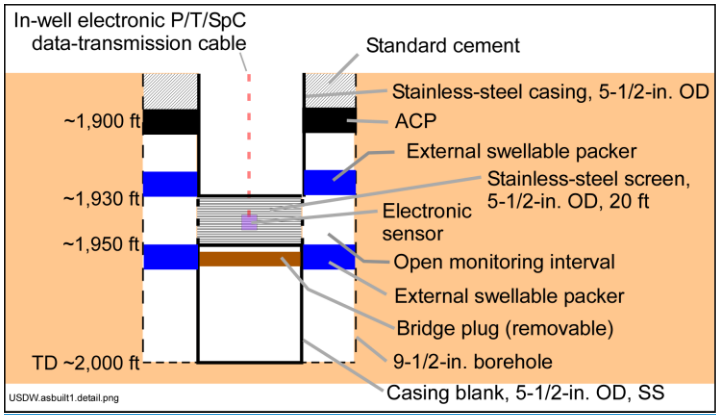

**Figure B-4. Construction Detail for USDW1**

**Table B-2. Casing and Borehole Program for the USDW Monitoring Well**

| Section | Borehole Depth (ft) | Borehole Diam. (in.) | Casing OD (in.) | Casing Grade | Casing weight (lb/ft) | Casing Connection |
|---|---|---|---|---|---|---|
| Conductor Casing | 150 | 20 | 16 | B | 55 | PEB |
| Surface Casing | 600 | 14-3/4 | 10-3/4 | J-55 | 40.5 | BTC |
| Intermediate Casing | NA | NA | NA | NA | NA | NA |
| Long Casing (with 20-ft-long screened section) | 2,000 | 9-1/2 | 5-1/2 | J-55 (0-1,700 ft); S13Cr110 (1,700–2,000 ft)~~).~~ | 17 | LTC (J-55); Vam Top or similar (S13Cr110) |

Grade B is equivalent to line pipe; BTC = buttress thread connection; Cr = chromium; LTC = long thread connection; PEB = plain end beveled.

Notes:

Actual casing grades and weights may differ based on material available at the time of construction.

All depths are approximate and may be adjusted based on information obtained when the well is drilled.

As discussed above, the well will be developed by air lift prior to installing the downhole P/T/SpC probe. If necessary, further development via air lift or pumping may be conducted after the well has been completed. During development activities, groundwater samples will be collected and tested for turbidity and other field parameters to ensure adequate development.

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## SLR1 Well Construction and Drilling Information

As illustrated in Figure B-5, a 20-in.-diameter conductor casing within a 26- to 30-in. hole will be installed into the Pennsylvanian bedrock to 150 ft bgs. This will be followed by a 17-1/2-in. hole lined with 13-3/8-in. casing to ~600 ft before drilling a 12-1/4-in. hole lined with 9-5/8-in. intermediate casing into the top of the confining zone (Proviso member) to a depth of approximately 3,450 ft bgs. Next, cement grout will be emplaced, under pressure, in the annular space behind the 9-5/8-in. casing and around the casing shoe until it rises to the surface. This will be followed by a downhole cement bond log and pressure testing to ensure there are no leakage pathways behind the 9-5/8-in. casing or shoe. After testing the seal integrity of the 9-5/8-in. casing, an uncased 7-7/8-in. to 8-1/2-in. open borehole will be drilled to ~4,150 ft bgs. Once at total depth, the open portion of the borehole will be developed to remove all cuttings and drill fluids via circulation and pumping of formation water. Development will continue until all drilling mud has been effectively removed from the borehole wall and pumped water is clear of particulates. Following development, a final 5-1/2-in.-OD casing string will be installed and cemented in place. Once the casing installation is complete, the 5-1/2-in. casing and surrounding cement will be perforated over the interval between 4,000 and 4,100 ft bgs, creating a 100-ft monitoring interval within the injection zone.

The portion of the 5-1/2-in. casing that penetrates the reservoir and the Eau Claire caprock (from total depth to ~3,450 ft bgs) will be composed of corrosion-resistant alloy material (e.g., S13Cr110) (Figure B-6). Corrosion-resistant cement will be used to cement the final casing string across this same interval. This specially formulated type of cement is more finely ground than regular cement and thus resists $CO_2$ infiltration into the more-reactive cement pores. Above the caprock and overlying the $CO_2$ reservoir, regular cement will be used to seal the remainder of the 5-1/2-in. casing (i.e., above 3,450 ft). All other casing strings will be cemented with standard well cement. A summary of the borehole and casing program for the SLR1 well is provided in Table B-3.

**Table B-3. Casing and Borehole Program for the SLR1 Monitoring Well**

| Section | Borehole Depth (ft) | Borehole Diam. (in.) | Casing OD (in.) | Casing Grade | Casing weight (lb/ft) | Casing Connection |
|---|---|---|---|---|---|---|
| Conductor casing | 150 | 26 to 30 | 20 | B | 94 | PEB |
| Surface casing | 600 | 17-1/2 | 13-3/8 | J-55 | 61 | BTC |
| Intermediate casing | 3,450 | 12-1/4 | 9-5/8 | J-55 | 36 | STC |
| Long casing (with 100-ft perforated section) | 4,150 | 7-7/8 or 8-1/2 | 5 -1/2 | J-55 (0-3,450 ft); S13Cr110 (3,450-4,150 ft) | 17 | LTC (J-55); Vam Top or similar (S13Cr110) |
| Tubing | 4,100 | NA | 2-7/8 | 13Cr80 | 6.5 | EUE |

Grade B is equivalent to line pipe; BTC = buttress thread connection; Cr = chromium; EUE = externally upset end; LTC = long thread connection; PEB = plain end beveled; STC = short thread connection.

Notes:

Actual casing grades and weights may differ based on material available at the time of construction.

All depths are approximate and may be adjusted based on information obtained when the well is drilled.

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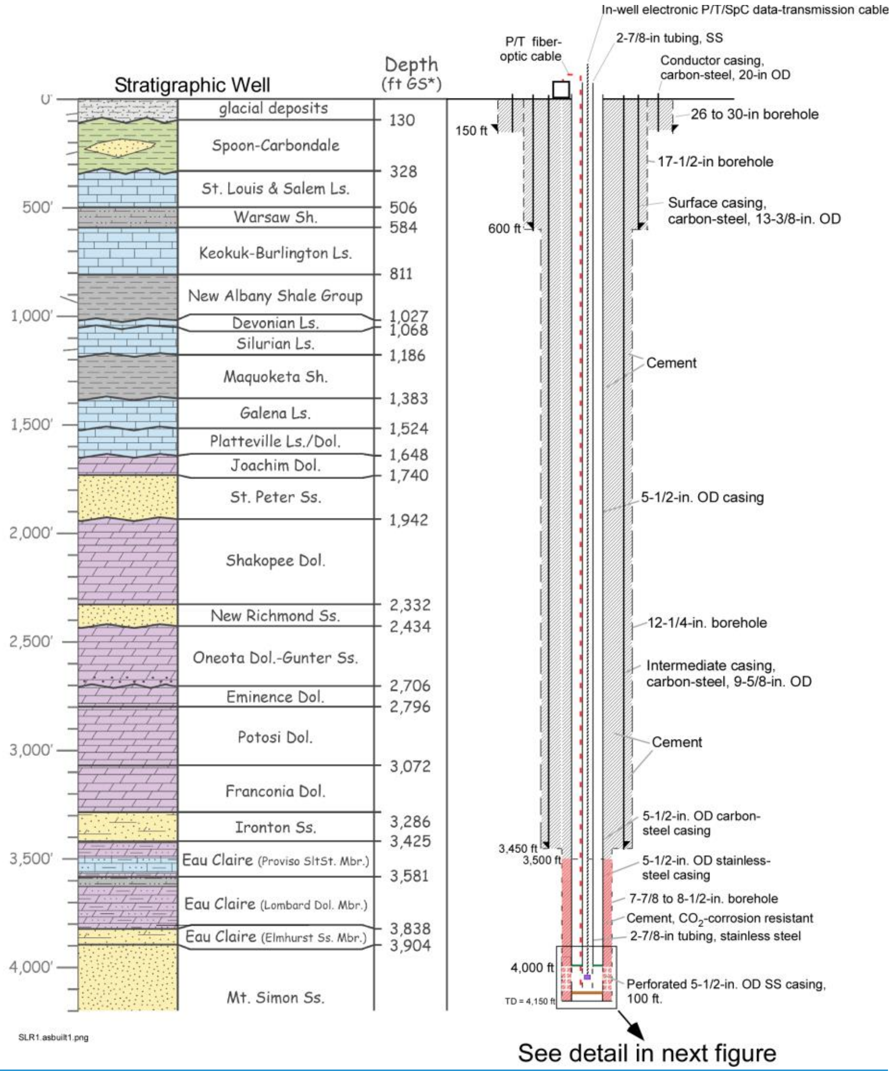

**Figure B-5 Construction Diagram for the New In-Reservoir Single-Level Monitoring Well (SLR1)**

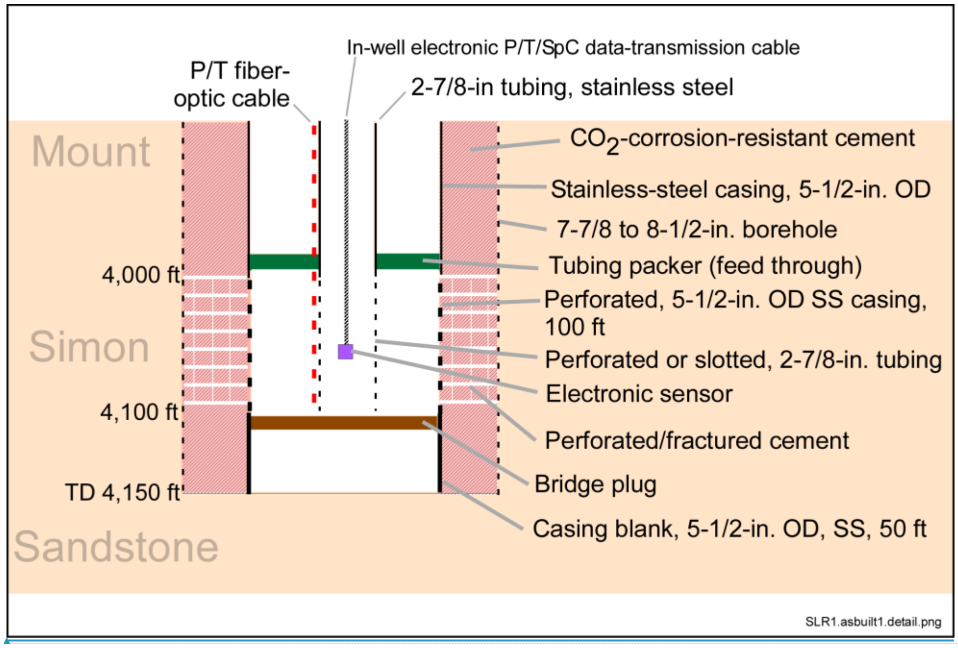

**Figure B-6. Construction Detail for SLR1**

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## SLR2 Well Construction and Drilling Information

Currently, the stratigraphic well is cased to 3,934 ft with 10-3/4-in. casing to below the top of the Mount Simon Sandstone (Figure ). Below this is a 14-3/4-in. open borehole to a depth of 4,018 ft, then a 9-1/2-in. borehole to a total depth of 4,812 ft, which extends approximately 400 ft into Precambrian basement rock. The borehole below the intermediate casing is currently uncased. The planned design for the reconfigured stratigraphic well (SLR2) includes backfilling the bottom 660 ft of the borehole with CO$_2$-resistant cement to ~4,150 ft (Figure ) before installing a 7-in.-OD casing string to 4,150 ft bgs. The 7-in casing will then be cemented in place using CO$_2$-resistant cement to near the top of the caprock (3,450 ft) followed by regular cement to the surface. The 7-in. well will be constructed using 7-in stainless steel (S13Cr110) casing to a depth of approximately 3,450 ft. Above this depth, carbon-steel casing will be used. After the cement job has been completed, the 7-in. casing and cement will be perforated to construct a 100-ft-long Mount Simon Sandstone monitoring interval between the depths of 4,000 and 4,100 ft. Following perforation and well development activities, a removable bridge plug may be installed just below the perforated interval to isolate it from the rathole below. A 2-7/8-in.-OD tubing string will then be run inside the 7-in. casing to near the bottom of the perforated interval. The installed tubing will be perforated (slotted) across the 4,000- to 4,100-ft-depth interval and isolated to this zone via a tubing packer above (Figure B-8). A summary of the borehole and casing program for the SLR2 well is provided in Table B-4.

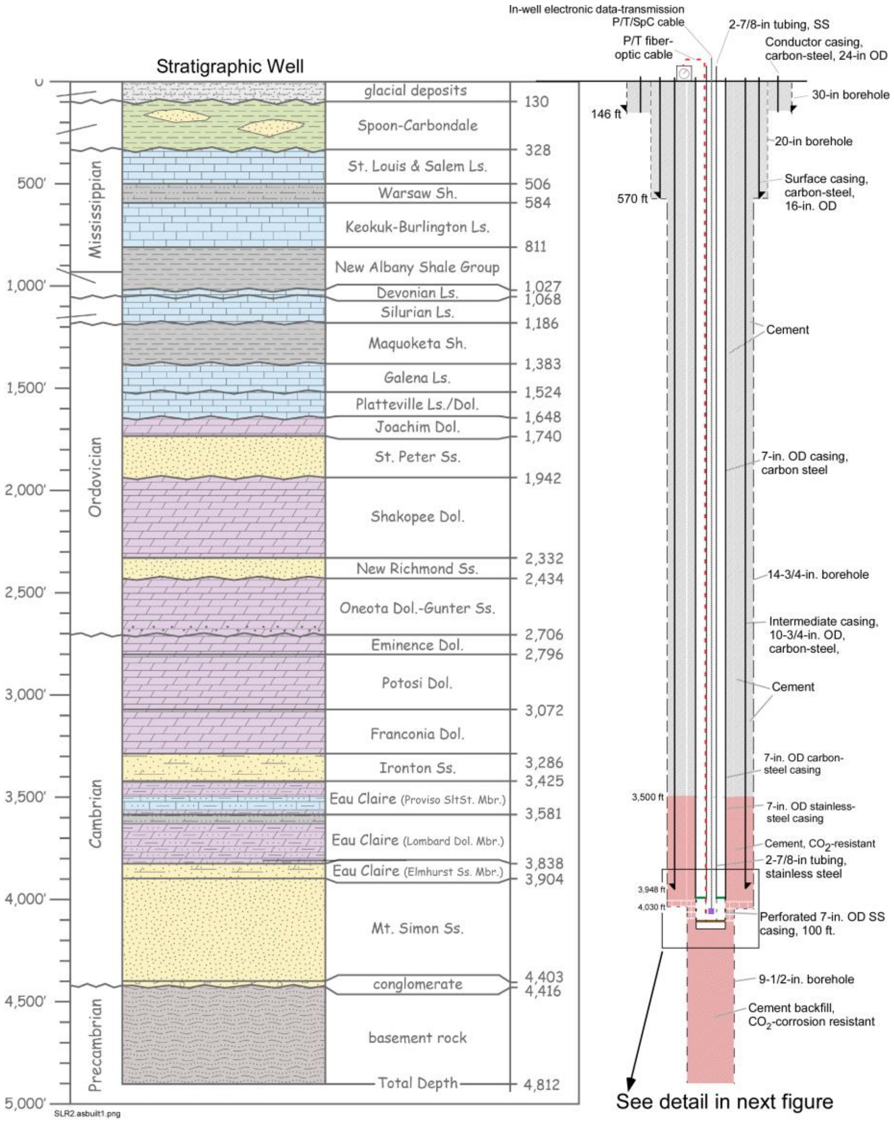

**Figure B-7.** **Construction Diagram for the Stratigraphic Well Reconfigured as an in-Reservoir Single-Level Monitoring Well (SLR2)**

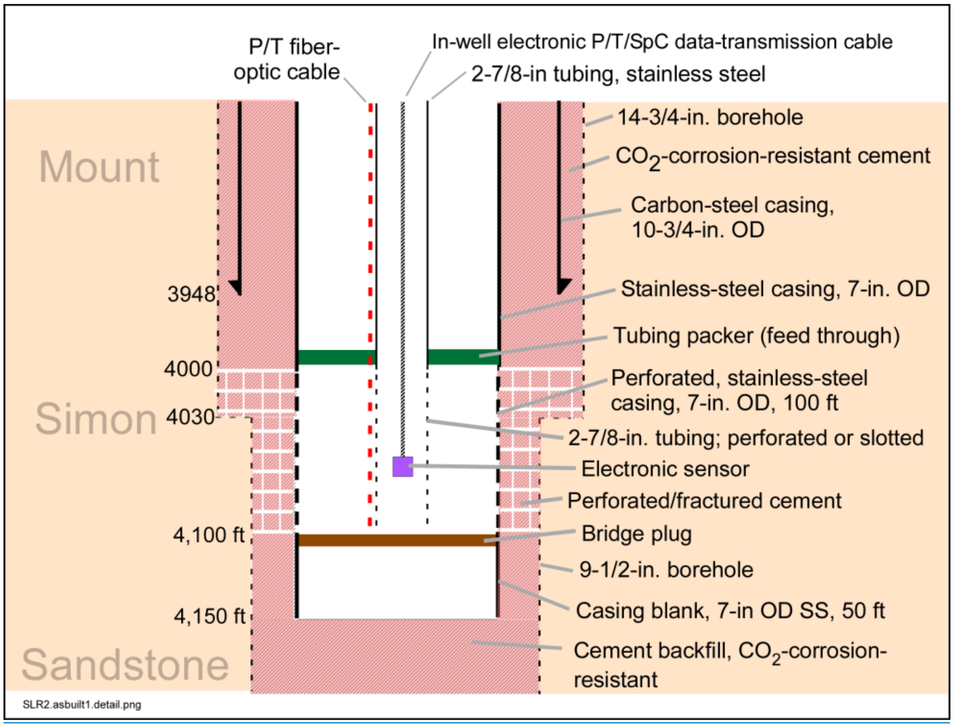

**Figure B-8. Construction Detail for SLR2**

**Table B-4. Casing and Borehole Program for the SLR2 Monitoring Well**

| Section | Borehole Depth (ft) | Borehole Diam (in.) | Casing OD (in.) | Casing Grade | Casing weight (lb/ft) | Casing Connection |
|---|---|---|---|---|---|---|
| Conductor casing | 132 | 30 | 24 | PEB | 140 | Welded |
| Surface casing | 556 | 20 | 16 | J-55 | 84 | BTC |
| Intermediate casing | 3,934 | 14-3/4 | 10-3/4 | N-80 | 51 | BTC |
| Long casing (with 100-ft perforated section) | 4,150 | 9-1/2 to 14-3/4 | 7 | N-80 (0-3,500): S13Cr110 (3,500-TD) | 29 | LTC (N-80); VAM TOP (S13Cr110) |
| Tubing | 4,100 | NA | 2-7/8 | 13Cr80 | 6.5 | EUE |

BTC = buttress thread connection; Cr = chromium; EUE = externally upset end; LTC = long thread connection; PEB = plain end beveled.

Note: Actual casing grades and weights may differ based on material available at the time of construction.

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## RAT Well Construction and Drilling Information

The monitoring network will also include three RAT installations (Figure B-9). 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. The RAT installations are planned for the collection of pulsed-neutron capture logs of the FutureGen $CO_2$ reservoir—the Mount Simon Sandstone. Design and construction requirements for the RAT installations are discussed in the following paragraphs.

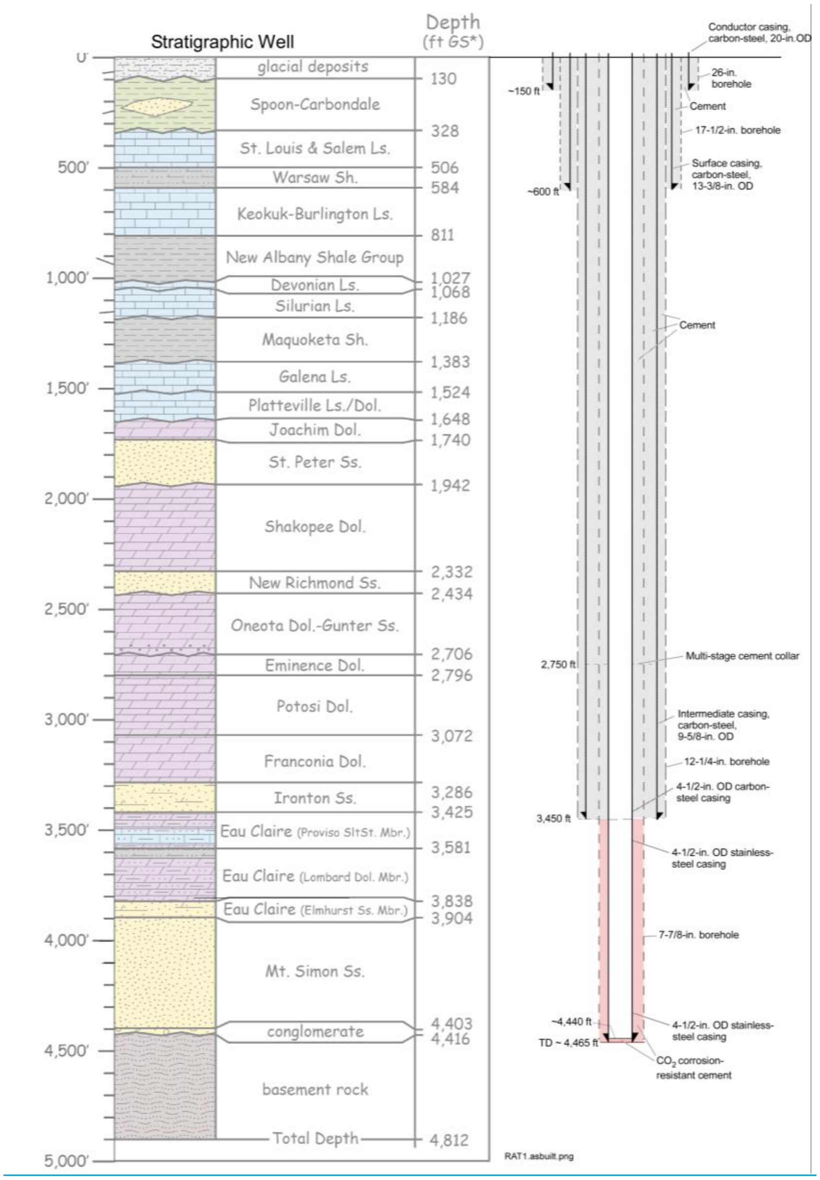

**Figure B-9. Construction Diagram for the Three Reservoir Access Tube ~~(RAT)~~ Installations**

To begin, a 26-in. borehole will be drilled and 20-in.-OD conductor casing will be installed to near the contact with Pennsylvanian bedrock (150 ft) (Figure B-10). Next, the boring will step down to a 17-1/2-

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**Formatted:** Font: 10 pt, Font color: Accent 6 in. borehole and 13-3/8-in. casing to approximately 600 ft. Below 600 ft, the hole will step down to a 12-1/4-in. hole lined with 9-5/8-in. casing down to the top of the confining unit (~3,450 ft) into the Proviso member. After cementing the 9-5/8-in. casing in place a 7-7/8-in. borehole will be drilled into the Precambrian basement rock (~4,465 ft). Next, a 4-1/2-in. stainless-steel casing will be lowered to the bottom of the hole and surrounded by $CO_2$-resistant cement, which will be allowed to rise 25 ft up inside the bottom of the 4-1/2-in. casing. Because these access tubes are designed for geophysical monitoring, no open interval will exist for direct measurement or collection of water samples or parameters. See Table B-5 for the RAT casing and borehole program details.

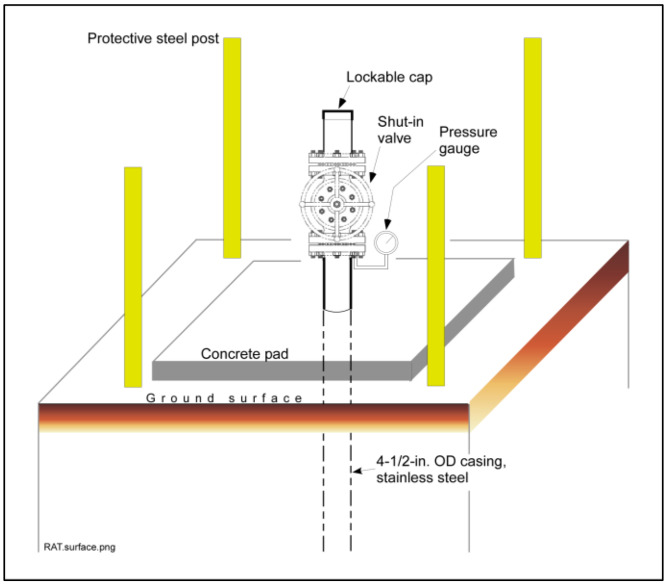

**Figure B-10. Surface Completion Diagram for Reservoir Access Tube ~~(RAT)~~ Installations**

The surface completion for the RAT installations will consist of a wellhead centered over a concrete pad. The wellhead will include a main shut-in valve and pressure gauge. The top of the access tube will be secured with a lockable cap along with four removeable steel protective posts outside each corner of the concrete pad.

**Table B-5. Casing and Borehole Program for the Reservoir Access Tubes**

| Section | Borehole Depth (ft) | Borehole Diameter (in.) | Casing OD (in.) | Casing Grade | Casing weight (lb/ft) | Casing Connection |
|---|---|---|---|---|---|---|
| Conductor Casing | 150 | 26 to 30 | 20 | B | 94 | PEB |
| Surface Casing | 600 | 17 1/2 | 13 3/8 | J-55 | 61 | BTC |
| Intermediate Casing | ~3,450 | 12 1/4 | 9 5/8 | J-55 | 36 | STC |
| Long Casing | ~4,465 | 7 7/88 to 8 1/2 | 4 1/2 | J-55 (0-3,500 ft);<br>S13Cr110 | 10.5 | STC |

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| | | |
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| | | (3,500-4,465 ft.) |

Grade B is equivalent to line pipe; BTC = buttress thread connection; Cr = chromium; LTC = long thread connection; PEB = plain end beveled.

Notes:

Actual casing grades and weights may differ based on material available at the time of construction.

All depths are approximate and may be adjusted based on information obtained when the well is drilled.

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# Attachment C

## Locations of Surficial Aquifer Monitoring Wells

| **Well ID** | **Well Type** | **Latitude** | **Longitude** |
|---|---|---|---|
| **FG-1** | FutureGen Shallow Monitoring Well | 39.80675 | -90.05283 |
| **FGP-1** | Private Well | 39.79888 | -90.0736 |
| **FGP-2** | Private Well | 39.78554 | -90.0639 |
| **FGP-3** | Private Well | 39.79497 | -90.0746 |
| **FGP-4** | Private Well | 39.79579 | -90.0747 |
| **FGP-5** | Private Well | 39.81655 | -90.0622 |
| **FGP-6** | Private Well | 39.81086 | -90.057560 |
| **FGP-7** | Private Well | 39.81444 | -90.065241 |
| **FGP-9** | Private Well | 39.80829 | -90.0377 |
| **FGP-10** | Private Well | 39.81398 | -90.0427 |

# Attachment D

## Locations of Permanent Gravity Stations

| Station# | Latitude | Longitude | |
|---|---|---|---|
| 0 | 39.73424 | -90.22926 | = NGS PID#KC0540, monument at Central Plaza Park, Jacksonville - point tied to 137 on 11/10/11 - this will be the reference to use in future surveys. |
| 5 | 39.79266 | -90.07426 | Nailed Permanent Stations |
| 21 | 39.79449 | -90.07424 | |
| 37 | 39.79617 | -90.07425 | |
| 53 | 39.79814 | -90.07427 | |
| 65 | 39.79991 | -90.08316 | |
| 66 | 39.79990 | -90.08090 | |
| 67 | 39.79989 | -90.07886 | |
| 68 | 39.79988 | -90.07616 | |
| 69 | 39.79989 | -90.07384 | |
| 83 | 39.80164 | -90.07889 | |
| 86 | 39.80176 | -90.07240 | |
| 99 | 39.80349 | -90.07888 | |
| 102 | 39.80352 | -90.07239 | |
| 107 | 39.80348 | -90.05998 | |
| 108 | 39.80295 | -90.05766 | |
| 109 | 39.80332 | -90.05519 | |
| 110 | 39.80339 | -90.05277 | |
| 115 | 39.80526 | -90.07887 | |
| 118 | 39.80529 | -90.07237 | |
| 126 | 39.80544 | -90.05216 | |
| 131 | 39.80710 | -90.07886 | |
| 134 | 39.80721 | -90.07154 | |
| 135 | 39.80720 | -90.06922 | |
| 136 | 39.80720 | -90.06687 | |
| 137 | 39.80727 | -90.06485 | |
| 147 | 39.80888 | -90.07885 | |
| 153 | 39.80842 | -90.06413 | |
| 154 | 39.80894 | -90.06224 | |
| 163 | 39.81078 | -90.07885 | |
| 171 | 39.81077 | -90.06002 | |
| 179 | 39.81248 | -90.07884 | |
| 187 | 39.81265 | -90.05999 | |
| 188 | 39.81283 | -90.05770 | |
| 189 | 39.81286 | -90.05538 | |
| 193 | 39.81447 | -90.08326 | |
| 194 | 39.81447 | -90.08103 | |
| 195 | 39.81451 | -90.07870 | |
| 196 | 39.81449 | -90.07629 | |
| 197 | 39.81457 | -90.07419 | |
| 205 | 39.81443 | -90.05513 | |
| 206 | 39.81436 | -90.05287 | |

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| Station# | Latitude | Longitude | |
|---|---|---|---|
| **207** | 39.81435 | -90.05064 | |
| **208** | 39.81437 | -90.04825 | |
| **213** | 39.81609 | -90.07408 | |
| **229** | 39.81790 | -90.07408 | |
| **245** | 39.81971 | -90.07407 | |
| **246** | 39.79996722210 | -90.08494295 | Permanent Stations to be added |
| **247** | 39.79997642140 | -90.08680687 | |
| **248** | 39.79998533330 | -90.08861842 | |
| **249** | 39.79999393550 | -90.09043265 | |
| **250** | 39.80000198450 | -90.09213566 | |
| **251** | 39.80001079270 | -90.09400542 | |
| **252** | 39.80001951540 | -90.09586339 | |
| **253** | 39.80003000000 | -90.09810508 | |
| **254** | 39.81088084490 | -90.09544073 | |
| **255** | 39.81088937800 | -90.09358759 | |
| **256** | 39.81211009600 | -90.0932439 | |
| **257** | 39.81361707930 | -90.0931657 | |
| **258** | 39.81450582940 | -90.09142522 | |
| **259** | 39.81450590850 | -90.08939647 | |
| **260** | 39.81450595100 | -90.08745444 | |
| **261** | 39.81450596010 | -90.0853458 | |
| **262** | 39.79094794920 | -90.07434558 | |
| **263** | 39.78955807990 | -90.07434813 | |
| **264** | 39.78808280800 | -90.07435083 | |
| **265** | 39.78655838880 | -90.07435362 | |
| **266** | 39.78543344990 | -90.08777897 | |
| **267** | 39.78542392910 | -90.08587085 | |
| **268** | 39.78541218410 | -90.0835256 | |
| **269** | 39.78540044900 | -90.08119175 | |
| **270** | 39.78540873070 | -90.07875712 | |
| **271** | 39.78542609070 | -90.07656216 | |
| **272** | 39.78533023230 | -90.07434254 | |
| **273** | 39.78541496330 | -90.07234073 | |
| **274** | 39.78538771320 | -90.07041894 | |
| **275** | 39.78537326690 | -90.06835921 | |
| **276** | 39.78537180190 | -90.06658679 | |
| **277** | 39.78537006050 | -90.06452139 | |
| **278** | 39.78536811720 | -90.06226638 | |
| **279** | 39.78533703980 | -90.06040206 | |
| **280** | 39.78532614220 | -90.05850696 | |

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# Attachment E

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## Locations of Microseismic Monitoring Stations and Integrated Deformation Stations

| Well ID/Station ID | Well / Station Type | Latitude (WGS84) | Longitude (WGS84) |
|---|---|---|---|
| **MS1** | · Microseismic monitoring Station 1(shallow borehole)<br>· Integrated deformation monitoring station | 39.8110768 | -90.09797015 |
| **MS2** | · Microseismic monitoring Station 2 (shallow borehole)<br>· Integrated deformation monitoring station | 39.78547402 | -90.05028403 |
| **MS3** | · Microseismic monitoring Station 3 (shallow borehole)<br>· Integrated deformation monitoring station | 39.81193502 | -90.06016279 |
| **MS4** | · Microseismic monitoring Station 4 (shallow borehole)<br>· Integrated deformation monitoring station | 39.78558513 | -90.09557015 |
| **MS5** | · Microseismic monitoring Station 5 (shallow borehole)<br>· Integrated deformation monitoring station | 39.80000524 | -90.07830287 |
| **ACZ1** | · Deep microseismic station (deep borehole) | 39.80034315 | -90.07829648 |
| **ACZ2** | · Deep microseismic station (deep borehole) | 39.80029543 | -90.08801028 |