KANSAS GEOLOGICAL SURVEY
The University of Kansas

File C - Proposed Testing and Monitoring Plan

Note: This document contains Testing and Monitoring information for the Kansas Small Scale Test Wellington Field. The contents were extracted from the original KGS permit document that was prepared prior to the new EPA submission format introduced to KGS on June 3rd 2014. This explains why the information in this Testing and Monitoring document may contain references to figures, tables, and sub-sections in other permit sections that may not be included in this Testing and Monitoring document. Therefore, to facilitate the review process, the entire original permit application has been submitted as a separate document titled “L - Other Information Required by the UIC Program Director”, which also contains an Executive Summary, cover letter, application forms, complete table of contents, list of tables and figures, appendices, and a cross reference table which lists sub-sections that address all Class VI 40 CFR sections 146.82 – 146.93 requirements.

The Proposed Testing and Monitoring Plan is documented in the following section:

A Research and Service Division of the University of Kansas
1930 Constant Avenue | Lawrence, KS 66047-3724 | (785) 864-3965 | Fax 785-864-5317 | www.kgs.ku.edu

Table of Contents

File C: Proposed Testing and Monitoring Plan

Section 10

Injection Well Testing and Pressure/Plume Front Monitoring Plan

Facility Information

Facility Name: Wellington Field Small Scale Carbon Capture and Storage Project

Injection well Location: Latitude 37.319485, Longitude -97.4334588

Township 31S, Range 1W, Section 28 NE SW SE SW

Facility Contact: Dana Wreath, Vice President

Contact Information: 2020 N. Bramblewood Street

Wichita, KS 67206

(316) 265-3311

Fax: (316) 265-8690

10.1 Introduction

40 CFR Part 146.90 requires the owner/operator to prepare, maintain, and comply with a testing and monitoring plan to verify that geologic injection and storage of CO_2 is operating as permitted and is not endangering USDWs. At a minimum, testing/monitoring must include:

- Analysis of the CO_2 stream,
- Installation and use of continuous recording devices to monitor injection pressure, rate, and volume; the pressure on the annulus between the tubing and the long string casing; and the annulus fluid volume added;
- Corrosion monitoring;
- Periodic monitoring of the groundwater quality and geochemical changes above the confining zone;
- A demonstration of external mechanical integrity pursuant to §146.89(c) at least once per year until the injection well is plugged; and, if required by the director, a casing inspection log pursuant to requirements at §146.89(d) at a frequency established in the testing and monitoring plan;

- A pressure fall-off test at least once every five years;
- Testing and monitoring to track the extent of the CO_2 plume and the presence or absence of elevated pressure using direct and indirect methods;
- Surface air/soil gas monitoring, if required by the director.

The Wellington project is funded by a cooperative agreement between the U.S. DOE and the Kansas Geological Survey and their cost-share partners as an experimental pilot-scale CCS project and, therefore, subject to funding availability, may include monitoring activities not mandated by Class VI regulations. These additional monitoring activities are specified in Appendix G. The mandatory monitoring activities to be conducted to meet Class VI requirements are specified in this section.

In addition to testing and monitoring at the injection well site (KGS 1-28), pressure and plume-front monitoring activities will be conducted at the Arbuckle observation well (KGS 2-28), two existing Mississippian wells above the primary confining zone, and two new Upper Wellington Formation (USDW) wells (Figure 10.1). A schedule of the testing and monitoring activities and frequency before, during, and after injection are listed Table 10.1.

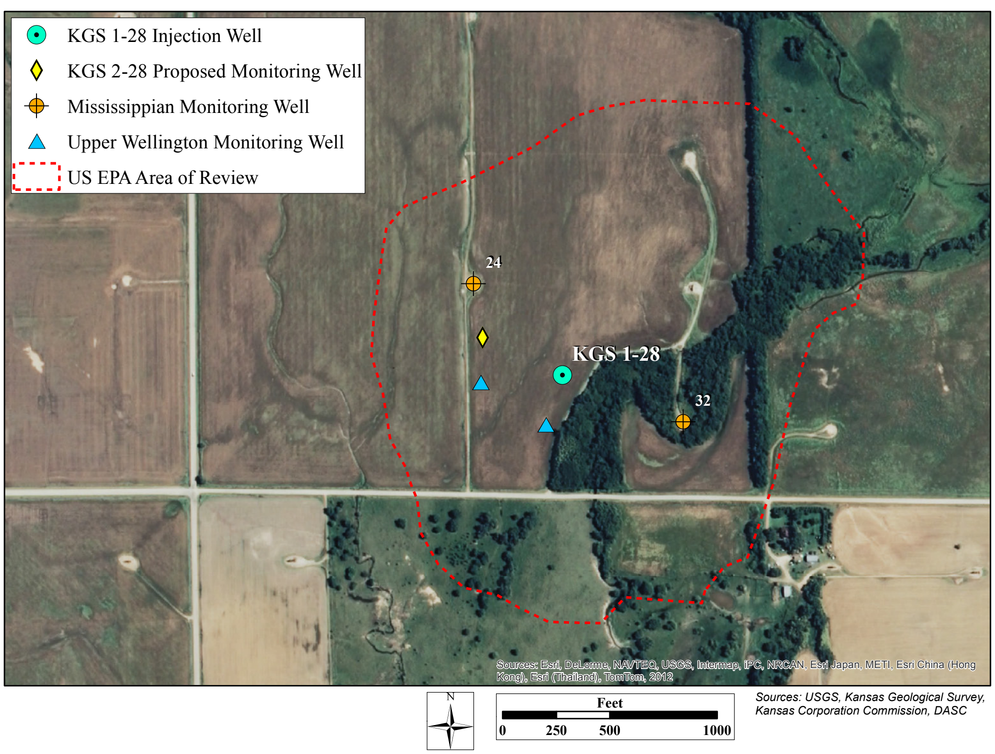

Figure 10.1—Location of monitoring wells in the Arbuckle, Mississippian, and Wellington formations.

The monitoring well construction plans are documented in Section 10.2. The well testing and pressure/plume-front monitoring plans are discussed in sections 10.3–10.5.

Table 10.1—Listing of monitoring activities to be conducted at the Wellington, Kansas, CO_2 storage site.

Monitoring Activity	Pre-Injection	Injection	Post-Injection
CO_2 Fluid Chemical Analysis	x	x	-
CO_2 Injection Rate and Volume[1]	-	x	-
CO_2 Injection Pressure at Wellhead[1]	-	x	-
CO_2 Injection Pressure at Well Bottom[1]	x	x	x
Internal MIT (Anulus Pressure Test)	x	-	-
External MIT (Temperature Log)	x	x	x
Continuous Annular Pressure	-	x	-
Corrosion	-	x	x
Pressure Fall Off Test	x	-	-
Pressure in Arbuckle Monitoring Well (Direct Arbuckle Monitoring)	x	x	x
INSAR (Indirect Arbuckle Pressure Monitoring)	x	x	x
USDW Geochemistry	x	x	x
Mississippian Geochemistry	x	x	x
U-Tube (Direct Arbuckle Geochemistry Monitoring)	x	x	x
CASSM (Indirect Arbuckle Plume-Front Monitoring)	x	x	x[2]
Crosswell Seismic (Indirect Arbuckle Plume-Front Monitoring)	x	x	-
3D Seismic Survey (Indirect Arbuckle Plume-Front Monitoring)	x	-	x

[1] Monitored continuously
[2] If CO_2 plume is detected at KGS 2-28 during the injection phase, then CASSM will not be conducted during the post-injection phase.

10.2 Monitoring Well Construction Information and Justification for Well Placement

A total of five monitoring wells will be used for tracking the CO_2 plume and pressure front. The locations of these monitoring wells and the formations that they will monitor are shown in Figure 10.1. One monitoring well is located in the Arbuckle aquifer. Two existing Mississippian wells will be used to check whether CO_2 has escaped upward from the primary confining zone (base of Simpson Group to top of Pierson formation) at the site. Two shallow wells will monitor water quality in the Upper Wellington Formation (lowermost USDW). The well design and construction plans for the monitoring wells are discussed below.

10.2.1 KGS 2-28 Arbuckle Monitoring Well

As shown in Figure 10.1, one monitoring well (KGS 2-28) is proposed to monitor CO_2 plume movement and pressure-front expansion in the Arbuckle Group. The well will be constructed approximately 400 ft updip of the injection well KGS 1-28 and will be used to facilitate direct and indirect monitoring of both the pressure front and CO_2 plume in the Arbuckle. The well will be constructed in full compliance with Class VI standards to ensure containment of CO_2, and a full suite of geophysical logs will be obtained. Based on modeling results, it is projected that the plume will reach the well in approximately 60–75 days after commencement of injection. Since the injection is to occur for only nine months, data obtained from this well will be sufficient to monitor and evaluate the movement of CO_2 within the Arbuckle Group, ensuring compliance with Class VI standards.

As discussed in Section 4.6.1 and shown in Figure 4.20, there is remarkable similarity in the geologic formations at well sites KGS 1-28 and KGS 1-32, which are located approximately 3,500 feet apart. Therefore, the geologic horizons at KGS 2-28 are also expected to be very similar to that at KGS 1-28. Hence, the proposed design of KGS 2-28 presented in Figure 10.2 is very similar to the injection well, KGS 1-28[1]. The well is expected to be approximately 5,300 feet deep, penetrating the top of the Precambrian granitic basement rock underlying the Arbuckle aquifer. The well will be perforated in the injection zone at approximately the same depth as the injection well (KGS 1-28) shown in Figure 8.1. The final depth and perforation interval will be established on completion of drilling and will be specified in the well completion report. The wellbore trajectory will be monitored every 1,000 ft to ensure that the deviations are minimal.

10.2.1.1 KGS 2-28 Wellbore and casing

The planned borehole and casing specifications at KGS 2-28 are shown in Table 10.2 and Figure 10.2. The conductor casing is expected to run between the surface and 125 ft. The surface casing, designed to provide a continuous cement sheath to fully isolate the USDW from the well,

1 It is expected that the kelly bushing (KB) reference elevation at the site will be 13 ft above ground, which would be similar to the condition at the existing injection well, KGS 1-28. All elevations in Figure 10.2 are sub-KB.

Wellbore Diagram

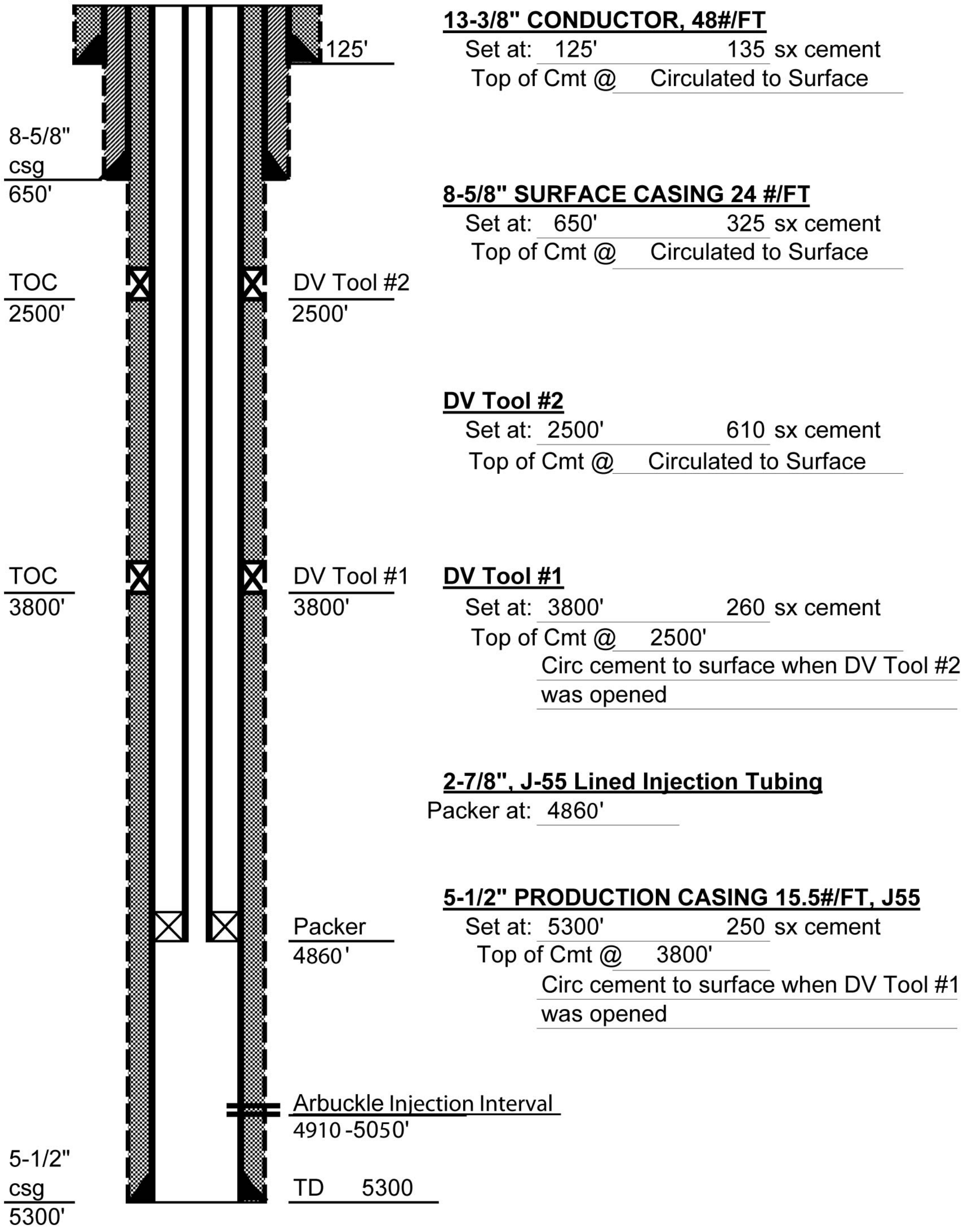

Figure 10.2—Well design schematic of the proposed Arbuckle monitoring well KGS 2-28.

Table 10.2—Projected borehole and casing specifications at KGS 2-28.

Casing	Depth Interval (ft)	Borehole Diameter (inches)	Size OD/ID (in)	Weight (lb/ft)	Grade	Connection Type	Collapse Pressure (psi)	Burst Pressure (psi)	Tensile Yield (lbs)	Thread Yield
Conductor	surface: 125	17.5	13-3/8 / 12.615	54	J55	ST&C	1,130	2,730	853,000	514,000
Surface	surface: approximately 650	12.25	8-5/8 / 7.972	24	J55	ST&C	1,370	2,950	381,000	244,000
Production	surface: approximately 5,300	7.875	5.5 / 4.892	15.5	J55	ST&C	4,040	4,810	248,000	222,000

runs from the surface to a depth of approximately 650 ft, well below the lowermost USDW (Upper Wellington Formation), which is expected to be in the top 250 ft at the site. All casing strings are designed as carbon steel. Corrosion of carbon steel casing is not expected during the life of this well. However, the potential for corrosion of casing material will be addressed by using CO_2-resistant cement as discussed below, and the well will be monitored for signs of corrosion as specified in Section 10.3.3.

10.2.1.2 KGS 2-28 Tubing

The tubing will consist of a 2.875 inch steel. It is expected to be approximately 5,000 ft long and weigh approximately 32,000 lbs, which is substantially less the maximum allowable joint yield strength of approximately 72,580 lbs (Table 10.3). This provides a safety margin at the uppermost joint of slightly more than 40,000 lbs if one assumes the axial load is being carried only by that joint

There will be approximately 2.5 inches of spacing between the production casing and the tubing, which is sufficient for work-over tools and conducting the testing and monitoring activities described in sections 10.4–10.5.

10.2.1.3 KGS 2-28 Cement

The conductor and surface casing cement job will be completed in a single stage. The cementing for the production casing will be accomplished in three stages using two DV tools at approximately 3,800 (DV #1) and 2,500 (DV #2) ft to ensure proper cement adherence (Figure 10.2). The cement will be circulated to the surface by opening DV Tool #1 and DV Tool #2 during cementing of the lowest and middle stages respectively. The lower cement stage covers the entire Arbuckle formations. Centralizers are expected to be used to properly align the casing and to ensure that they are completed sealed.

As shown in Table 10.4, common portland cement will be used to seal the space in the borehole for the conductor casings, and 60/40 Pozzolanic cement is to be used for the surface

Table 10.3 —Tubing specifications at KGS 2-28.

Name	Depth (ft)	Wall Thick-ness (in)	Inside Diameter (in)	Weight (lb/ft)	Grade (API)	Design Coupling (Short or Long Thread)	Burst Strength (psi)	Collapse Strength (psi)	Joint Yield Strength (lb)	Body Yield Strength (lb)
Injection Tubing	surface: approximately 4,860 ft	0.217	2.441	6.4	J55	Non upset	7,260	7,680	72,580	99,661

casing. For the conductor casing, CO_2-resistant cement AA-2 will be used in the bottom stage, a combination of AA-2 and CO_2-resistant A-Con will be used in the middle stage, and AA-Con will be used in the top stage. Note that the cement quantities specified in Table 10.4 are estimates and may be adjusted as a result of hole conditions, depths, etc.

Table 10.4—Cement specifications for Arbuckle monitoring well KGS 2-28.

Purpose of String	Size Hole Drilled (in)	Size Casing Set (in)	Weight (lb/ft)	Setting Depth (bls, ft)	Type of Cement	Number of Sacks Used	Type and Percent Additives
Conductor	17.5	13.375	48	125	Common	135	3%cc, ¼# flake
Surface	12.25	8.625	24	Approximately 650	60/40 POZ	325	3%cc, ¼# flake
Production	7.875	5.50	15.5	Approximately 5,300	AA-2	250	10% salt, 6 #gils, C-44
1st DV Tool	7.875	5.50	15.5	Approximately 3,800	A-Con & AA-2	260	10% salt, 6 #gils, C-44
2nd DV Tool	7.875	5.50	15.5	Approximately 2,500	A-Con	610	10% salt, 6 #gils, C-44

10.2.1.4 Geophysical Data Acquisition and Analyses

A modern suite of wireline logs such as "triple combo," full-wave sonic samples will be acquired at the monitoring borehole to obtain necessary petrophysical information (i.e., porosity, saturation, and sonic velocity). The triple combo logs will include neutron density, gamma ray, caliper, SP, photo electric, and resistivity logs. Analysis of wireline logs will involve calibration with core measurements to predict porosity and permeability; estimation of rock mechanical properties from dipole sonic waveforms; and evaluation of formation invasion and resistivity to help in flow unit identification. The wireline data acquired at this site shall be integrated with log and core data from existing Arbuckle wells KGS 1-32 and KGS 1-28 to update the regional geomodel-based porosity and permeability distributions in the Arbuckle aquifer, if necessary. The geophysical data also will be used to establish the stratigraphy at the site and if it appears that the geologic formations at KGS 2-28 are offset with respect to KGS 1-28, then the perforation in the injection interval in the new monitoring well will be offset accordingly.

10.2.1.5 Borehole Testing

Drill-Stem Test

A drill-stem test will be run across the injection interval to estimate formation hydrogeologic properties and to sample formation water.

Swab Tests

The borehole will be perforated in the Arbuckle injection interval for collection of fluid samples. Geochemical analysis (Fe, Ba, Mn, SO_4, K, S, Mg, Sr, Ca, Cl, Na, Br, Si, NO_2, NO_3, Cu, Li and P; as well as pH, TDS) will be conducted on the samples to identify chemistry of formation water (cations, anions, TDS).

10.2.1.6 Demonstration of Mechanical Integrity

Mechanical integrity tests shall be carried out at the monitoring borehole to ensure proper setting of the cement and to minimize the risk of CO_2 leakage around the well bore. A cement bond log will be obtained after setting the long-string casing. A thermal log will be acquired to ensure integrity of the cement and casing. The absence of temperature spikes in the log will indicate the absence of substantial leaks in the cement and/or casing. An annulus pressure test will be conducted to ensure that there are no leaks in the packer, tubing, and casing. As discussed in Section 10.3.2.4, the annulus will be monitored daily for leaks during injection by checking the fluid level in the annulus.

10.2.2 Mississippian Monitoring Wells

10.2.2.1 Well Location and Justification for Site Selection

Several active oil wells around the CO_2 injection well KGS 1-28 are producing from the upper Mississippian formation immediately above the Pierson formation, which is part of the upper confining zone. The location of the two Mississippian wells that will be used as monitoring wells are presented in Figure 10.1. Well construction details of these two wells are presented in Table 10.5. No geophysical logs are available for these wells in the KGS database. Both wells were selected because they are in the updip direction as the Arbuckle generally dips southward. The Wellington Well Unit 24 is also the closest Mississippian well to the injection well (KGS 1-28).

Table 10.5—Well data for Mississippian wells to be used for CO_2 monitoring.

API Number	Lease Name	Well Class	Operator Name	Status	Spud Date	Completion Date	Total Depth (ft)	Elevation (ft, msl)	NAD83 Latitude	NAD83 Longitude
15-191-10045	Wellington Unit 32 (Was Kamas 6)	Producing	Sinclair Prairie Oil Co.	OIL	2/1/36	10/1/36	1246	1246	37.318829	-97.4316
15-191-10055	Wellington Unit 24 (Was Frank Kamas 9)	Producing	Sinclair Prairie Oil Co.	OIL	12/14/36	10/1/37	1264	1264	37.320713	-97.43501

Casing head gas and groundwater sampling of the Mississippian wells will be conducted during the pre-injection phase to establish respective background (baseline) readings. Thereafter, water and casing head gas shall be sampled on a periodic basis during the injection and post-injection phases, analyzed, and compared with the baseline survey data to detect the presence of CO_2 in the Mississippian reservoir. The water-quality monitoring plan and schedule are presented in Table 10.1 and Section 10.4.1.1.

10.2.3 Upper Wellington Formation (Lowermost USDW) Monitoring Wells

The Upper Wellington formation is present from near land surface to approximately 250 ft below ground. Based on the water table map presented in Figure 4.14, groundwater movement at the site is primarily toward Slate Creek south of the site. The general dip of the subsurface formation is also southward. Two monitoring wells will be placed in the Upper Wellington Formation: One well will be placed downstream and due south of KGS 1-28, and the second well will be located west of the injection well along the edge of the paved road as shown in Figure 10.1. These wells are expected to intercept any plume that may potentially move into the USDW. Both monitoring sites are located close to paved roads in the area, thereby providing easy access. The water-quality monitoring plan for the USDW is presented in Section 10.4.1.2.

10.2.3.1 USDW Monitoring Well Design

The two USDW monitoring wells (shown in Figure 10.1) will be screened approximately 120 ft below ground surface (Figure 10.3). Most existing groundwater wells in Sumner County are less than 120 ft deep. The final screen intervals, however, will be established after drilling at the site, with the goal to monitor the deepest zone in the USDW. Each well will be constructed of 2-in (internal diameter) Schedule 40 PVC constructed in a 6-in diameter boring and gravel packed across a 10- to 20-ft interval depending on screen location and lithology, which will be decided after completion of the drilling. The well will be fully grouted above and below the screened interval. Approximately 2–3 feet of bentonite seal will be placed on top of the gravel pack to assure a good seal before grouting. Each well will extend about 1.5 ft above ground surface with a pressure tight cap which will have a cap, with a hole for a 0.25-in tube and 0.5-in hole for access with field monitors (water-level meter, D.O., pH, etc.). The wells will have a steel protective housing and a 3-ft by 3-ft cement pad.

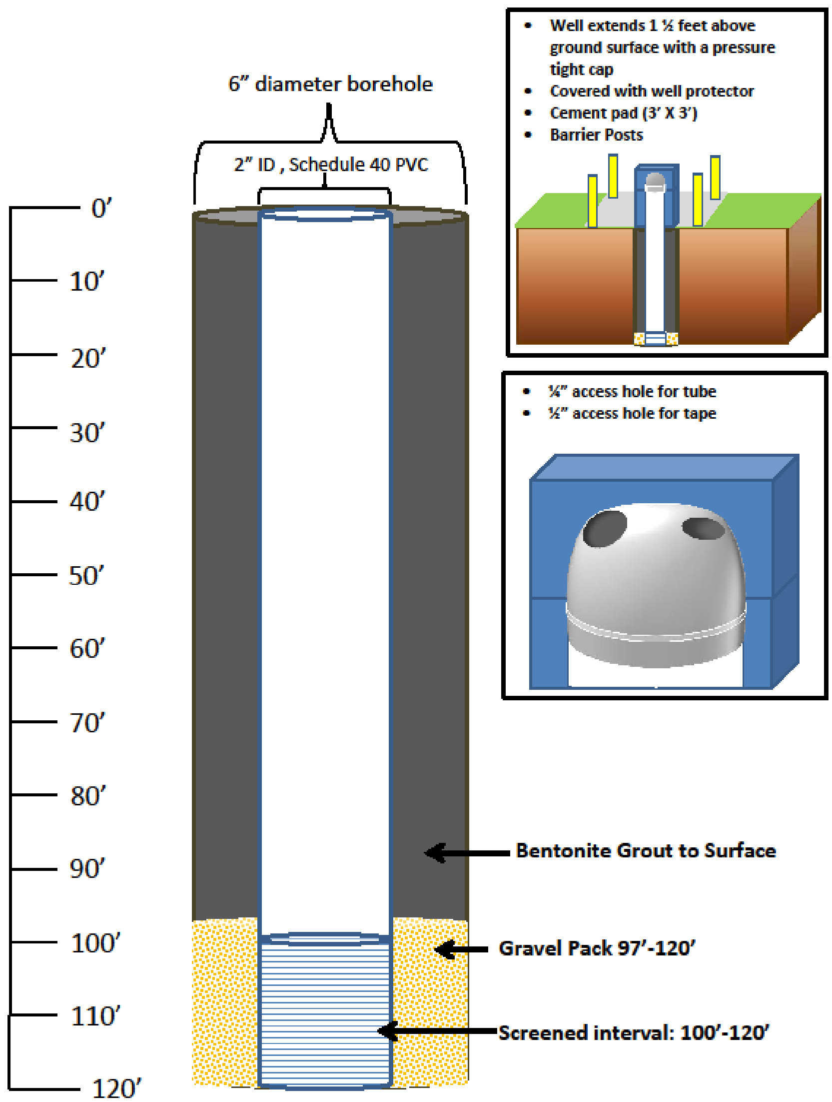

Figure 10.3 —Typical schematic of Upper Wellington Formation monitoring well showing screened interval at 100–200 ft below land surface.

10.2.3.2 Borehole Logs

Samples of soil in the Wellington Formation will be collected and analyzed by X-ray diffraction to obtain major mineralogy.

10.3 Testing and Monitoring at Injection Well Site

10.3.1 Carbon Dioxide Stream Analysis (§ 146.90 [a])

The Class VI rule requires that the injected CO_2 stream be analyzed with sufficient frequency to yield data representative of its chemical and physical characteristics (40 CFR 146.90[a]). Monitoring the chemical composition is accomplished to verify that the injectate does not qualify as hazardous waste with regard to corrosivity or toxicity, as well as to ensure that the delivered CO_2 stream meets the specifications outlined in the UIC permit. As indicated in Section 10.5.2, small quantities of tracer gases SF_6 (sulfur hexafluoride) and Kr (krypton) will be periodically co-injected with the CO_2 to facilitate estimation of the travel time between the injection and monitoring wells/boreholes.

10.3.1.1 Sampling Location and Method

CO_2 will be obtained from an ethanol plant or similar industrial source as described in Section 1. The CO_2 stream is expected to be composed of high purity (99+ %) CO_2. The CO_2 is expected to be water saturated and delivered at near atmospheric pressure. The CO_2 will be dehydrated and compressed to a liquid state at a temperature and pressure of approximately -10^{o}F and 350 psi and transported in trucks to the site for injection. CO_2 injectate samples will be collected immediately upstream of the injection well head in a lined sample bottle and transported to an approved laboratory for analysis.

10.3.1.2 Fluid Analysis

The exact chemical composition of CO_2 will be ascertained pre-injection. The CO_2 stream is expected to have high levels of CO_2 with only trace levels of other constituents or impurities such as nitrogen, oxygen, methanol, acetaldehyde, and hydrogen sulfide. The analytical suite will be established when the first pre-injection sample is collected and at a minimum will include nitrogen, oxygen, methanol, acetaldehyde, and hydrogen sulfide. The samples will be analyzed (by a certified laboratory) using standardized ASTM procedures for gas chromatography, mass spectrometry, detector tubes, and photo ionization. The sample will be tested using ASTM 5954, ASTM 6228, ASTM 5504, or equivalent procedures. For permitting purposes, it is proposed that the CO_2 stream will not exceed the minimum specification shown in Table 10.6.

Table 10.6—Minimum CO_2 Stream Acceptance Specifications (source: FutureGen, 2013).

Component	Quantity
CO_2	97% dry basis
Inert Constituents	1%
Trace Constituents	2%
Oxygen	<20 ppm
Total Sulphur	< 25 ppm
Arsenic	< 5 ppm [a]
Selenium	< 1 ppm [a]
Mercury	< 2 ppb [b]
Hydrogen Sulfide	< 20 ppm
Water Vapor	< 30 lb/mm scf

(a) Resource Conservation and Recovery Act (RCRA) standard

(b) Safe Drinking Water Act standard

CO_2 grab samples will be collected immediately upstream of the well head in a pre-cleaned lined sample bottle and transported to a laboratory for analysis. The bottle will be flushed with inline CO_2 before sample collection, labeled, and transported to the laboratory in accordance with EPA guidelines. A Chain of Custody form will document:

- Sampling date
- Analytical detection limit
- Location of the sample

- Type of container
- Sampler name and signature
- Other comments/notes
- Shipping information (name, address, and point of contact at laboratory, including phone number)
- Name and signature of personnel involved in the chain of custody.

The laboratory report will include the analytical results as well as detection limits established for the method employed to detect each chemical constituent presented in Table 10.6.

10.3.1.3 Sampling Frequency

The CO_2 is expected to have fairly uniform chemical composition throughout the year. Therefore, the CO_2 will be sampled at five periods: before commencement of injection, once each month for the first three months of injection, and again six months after commencement of injection. Injection is to cease at the end of nine months of operation. If there is significant variation in the quarterly sample results, then a final sample will be collected and analyzed at the end of the injection period (nine months).

10.3.1.4 Quality Assurance/Quality Control

The samples will be analyzed (by a certified laboratory) using standardized ASTM procedures for gas chromatography, mass spectrometry, detector tubes, and photo ionization. The sample will be tested using ASTM 5954, ASTM 6228, ASTM 5504, or equivalent procedures. The sample integrity and security will be documented through maintenance of a field sampling record and a Chain of Custody form as described above. The laboratory report will provide documentation of instrument calibration, analytical results, and detection limits established for methods employed. For data validation purposes, the following samples will be analyzed with each batch of collected samples:

- One or two field duplicates

- One equipment rinsate
- One matrix spike (when appropriate for the analytical method)
- One trip blank

10.3.2 Continuous Recording of Operational Parameters (§ 146.90 [b])

10.3.2.1 Continuous Monitoring of Injection Rate/Volume

The Class VI rule requires the installation and use of continuous recording devices to monitor injection rate and volume (40 CFR 146.88[e]). The monthly average, maximum, and minimum values will be reported in semi-annual reports (40 CFR 146.91[a][2]). This information will be used to verify compliance with the operational conditions of the permit and to assist in AoR re-evaluations.

The injection rate will be continuously monitored using the Orifice-Plate differential meter, which uses Bernoulli's equation to determine flow by measuring the pressure drop across a plate with a hole. It is the standard flow measuring device in the oil and gas industry and typically achieves an accuracy of 2–4% of the full-scale reading (EPA, 2012). The mass rate will be calculated using the CO_2 density, which will be calculated using equations of state and pressure and temperature readings. Cumulative injection volume and mass will be continuously calculated and reported in semi-annual reports. Because the CO_2 will be transported to the site via trucks, a direct measurement of the CO_2 mass will be available. Additionally, from a safety/environmental perspective, the maximum amount of CO_2 that can potentially escape into the atmosphere and geologic formation due to a sudden catastrophic well or surface infrastructure failure will be limited to the capacity of the storage tanks at the site, which will be slightly greater than 150 tons.

10.3.2.2 Continuous Monitoring of Injection Pressure

The Class VI rule requires the installation and use of continuous recording devices to monitor injection pressure (40 CFR 146.90[b]). Injection pressure will be measured at both the wellhead and the center of the perforations in the injection zone (bottomhole pressure). Bottomhole pressure is equal to wellhead pressure plus the hydrostatic pressure that exists due to the weight of the fluid column between the wellhead and bottom hole, minus frictional losses. The two sources of pressure data will therefore be used to check the accuracy of the individual pressure measurements. Injection pressure is monitored to ensure that the fracture pressure of the formation and the burst pressure of the well tubing are not exceeded and that the owner or operator is in compliance with the permit. A standard oil-filled pressure gauge will be installed at the wellhead, and a pressure transducer will be placed near the perforation to monitor the bottomhole pressure.

10.3.2.3 Continuous Monitoring of Temperature

Surface and bottomhole temperature will be monitored continuously in the injection well using the same data logger that measures pressure to fulfill injection well operating requirements stated in §146.88 e (1).

10.3.2.4 Continuous Monitoring of Annulus Pressure and Volume

Since a waiver is sought from pressurizing the annulus due to low injection pressures as discussed in Section 8.1, continuous monitoring of the annulus will involve a daily inspection of surface pressure in the annulus of the injection well. The corrosion-resistant fluid in the annulus will initially be filled to the surface. A change in pressure greater (or less) than expected due to temperature changes will be considered a failure of the internal MIT and will trigger a system-wide shut-off (40 CFR 146.88[e][2]), which will halt injection immediately and limit the amount of leakage. The shutoff will be reported to the EPA within 24 hours. The cause(s) of the pressure change will be investigated to identify the location of leakage and repair the well. An annulus pressure test will be conducted after investigation/remediation to ensure well integrity.

10.3.2.5 Operating Range for Key Injection Parameters

The operating range for key injection parameters are:

- CO_2 Injection Flow Rate: 150 metric tons/day (+/- 5%)

- Wellhead Inlet Pressure: < 800 psig
- Bottomhole Pressure: < 3,408 psig at 5,050 ft (90% of fracture gradient of 0.75 psi/ft)
- Annulus Pressure at Surface: 0 psig
- Wellhead CO_2 Temperature: -10º to +10º F
- Bottomhole CO_2 Temperature: 20–60º F at 5,050 ft

10.3.3 Corrosion Monitoring (§ 146.90 [c])

The Class VI rule at 40 CFR §146.90(c) requires quarterly monitoring of well materials for corrosion to detect loss of material in the casing, tubing, and packer that may compromise the mechanical integrity of wells. CO_2, in the presence of water leads to the formation of corrosive carbonic acid, which historically has been the primary cause of well failure in CO_2 injection wells (EPA, 2012). However, due to the short period of injection (nine months) and the construction of the Arbuckle wells in accordance with Class VI guidelines, corrosion is not expected to occur in the Wellington injection or observation wells.

10.3.3.1 Corrosion Detection Method and Sampling

Corrosion coupons will be used for monitoring loss of material in the injection well. Coupons are very simple to use and analyze, and they provide a direct measurement of material lost to corrosion (EPA, 2012). Two pre-weighed, dimensionally measured, and photographed coupons made of representative injection well construction material will be placed in the flow line and the wellhead. These coupons will be removed every quarter, cleaned, and reweighed. The samples will be visually inspected under magnification for loss of mass, thickness, cracking, pitting, or other signs of corrosion.

The average corrosion rate in the well will be calculated from the weight loss of the coupon.

The coupon will be weighed to an accuracy of +/- 0.1 of a milligram. The weight will be used to calculate the corrosion rate in mils/yr, where a mil is equal to a thousandth of an inch.

If the coupons are found to have more than 3 mils/yr of loss, corrective action will be taken in consultation with the EPA Region 7 director, and the coupons will be monitored more frequently. However, as mentioned above, no corrosion of the well material is expected given the short duration of injection.

10.3.3.2 Corrosion Reporting

Dimensional and mass data, along with a calculated corrosion rate (in mils/yr), will be submitted to the EPA program director every six months in semi-annual reports, which will include the following information:

- A description of the corrosion monitoring technique;
- Measurement of mass and thickness loss from corrosion coupons;
- Assessment of additional corrosion, including pitting, in the corrosion coupons and the overall corrosion trends;
- Any necessary changes to the project Testing and Monitoring Plan to continue protection of USDWs.

10.3.4 Mechanical Integrity Testing (§ 146.90 [e])

Internal and external mechanical integrity tests (MITs) will be conducted before, during, and after injection. Internal tests will be conducted to ensure the absence of any leaks in the injection tubing, packer, or casing, and external tests will be conducted to ensure the absence of any leaks through channels adjacent to the wellbore that may result in significant fluid movement into a USDW. The results of the tests, including a description of the methods employed and results of previous tests will be submitted to the EPA for review. The Class VI rule requires that internal mechanical integrity be demonstrated continuously during injection, and external MIT be conducted before injection, at least once per year during the injection phase, and before injection well plugging after the cessation of injection.

10.3.4.1 Internal MIT with Annulus Pressure Test

Before commencing injection, an annulus pressure test will be conducted at the injection well KGS 1-28 in order to demonstrate internal MIT. The test will provide information necessary to determine whether there is a failure of the casing-cement bond, injection tubing, and packers.

The test will consist of pressurizing the corrosion-resistant fluid of the annulus to 500 psi and then isolating the annular space from the source of pressure by a closed valve. Pressure measurements taken during isolation of the annulus will be analyzed for any change in pressure for 30 minutes to detect leakage. Because the annulus exchanges heat with its surroundings, small pressure changes that are not due to leakage may occur during the test.

After the test period, the valve to the annulus will be opened and the amount of returned fluid will be measured in a container. This will be a confirmatory exercise to determine whether the full length of the annulus was tested as the amount of captured liquid should be in conformance with the size of the annulus and the test pressure. The data obtained, including recorded charts from the tests and volume of liquid used, will be submitted to the EPA within 30 days of test completion as required in 40 CFR §146.91(b).

Failure of the pressure to stabilize within a range of 5 percent of the injection pressure will constitute a failure to demonstrate mechanical integrity. If this occurs, the causes of the pressure drop will be investigated and corrective measures implemented as necessary. An annulus pressure test will be conducted after any well remediation activities to confirm well integrity.

10.3.4.2 External MIT Using Temperature Logs

A temperature log will be used to demonstrate external MIT in the injection well (KGS 1-28), and its use is based on the principle that fluid leaking from the well will cause a temperature anomaly adjacent to the wellbore. The log will be obtained from the surface to the bottom of the well using a wireline logging tool.

Temperature logs will be obtained before commencement of injection, after 6 months of injection, and before closure of the site. The pre-injection log, along with the temperature log obtained during well construction, will serve as a baseline for the subsequent monitoring during the injection and post-injection phases.

As suggested in EPA guidance (EPA, 2012), the well will be shut during the injection phase for a period of 36 hours before obtaining the temperature log (EPA, 2012). During the shut-in period, the temperature within the wellbore will typically migrate towards ambient geothermal conditions but will not fully equilibrate to ambient conditions. If there has been a leak of fluid out of the well, the temperature within the wellbore at this location will change to a lesser extent and be measured as an anomaly because the temperature of the surrounding formation will have been modified by the leaking fluid.

Leaks will be identified from injection and post-injection logs by noting relative differences between the collected temperature log and the baseline (and previous) logs. Since lithology and injectate characteristics will be similar, the thermal effects along the wellbore are expected to be very similar. After the temperature effects caused by injection, casing joints, packers, well diameter, casing string differences, and cement have dissipated, the temperature profiles are expected to be similar, although not identical. The log and associated report will be submitted to the EPA within 30 days of test completion as required in 40 CFR §146.91(b). If interpretation of the data indicates a noncompliance, a report will be submitted to EPA within 24 hours of testing as required by § 146.91 (c). If necessary, radioactive tracer, noise, oxygen activation, or other logs approved by the UIC program director may be used to further define the nature of the fluid movement.

10.3.5 Pressure Fall-Off Testing (§146.90[f] and 40 CFR §146.87[e][1])

The Class VI rule requires pressure fall-off testing of the injection well before commencing injection (40 CFR §146.87[e][1]) and at least once every five years (40 CFR §146.90 [f]). Pressure fall-off tests are used to measure formation properties in the vicinity of the injection well. The objective of periodic testing is to monitor for any changes in the near-wellbore environment that may affect injectivity and pressure increase. Anomalous pressure drops during the test may also be indicative of fluid leakage through the wellbore.

A pressure fall-off test will be conducted before commencement of injection at the Wellington site. However, a pressure fall-off test after commencement of injection is not proposed for this project because a) injection is to occur for a short period of 9 months, b) extensive testing/monitoring to track the carbon dioxide plume will be performed, and c) the site is expected to close within 5 years of commencement of injection.

A steady rate of water flow will be maintained during the injection phase of the pressure fall-off test. This will be followed by a shut-in period, the duration of which will be determined on the site to obtain sufficient transient response for analyzing the data. The bottomhole pressure will be continuously recorded during the entire test by pressure transducers for a sufficient period to make valid observation of a pressure fall-off curve. Pressures will be measured at a frequency that is sufficient to measure the changes in bottomhole pressure throughout the test period, including rapidly changing pressures immediately after cessation of injection. The magnitude of the bottomhole pressure will be adjusted so as to not exceed 90% of the fracture gradient estimated in Section 4.6.9.

A report containing the pressure fall-off data and interpretation of the reservoir ambient pressure will be submitted to the U.S. EPA within 90 days of the test.

10.4 Groundwater Geochemical Monitoring Above the Confining Zone (§146.90 [d])

40 CFR §146.90 requires periodic monitoring of groundwater above the confining zone. Groundwater quality in the USDW (Upper Wellington Formation) and the upper Mississippian System above the confining zone will be directly monitored. Figure 10.1 shows the location of the Mississippian and USDW monitoring wells. Section 10.2 presents information pertaining to construction of the monitoring wells. All monitoring wells shown in Figure 10.1 are located close to paved roads and are fully accessible by truck. Berexco is the operator of the Wellington oil field and has permission to physically monitor all well sites.

Baseline data will be collected from the monitoring wells before injection, and monitoring will be conducted according to the schedule in Table 10.7. An increase in the concentration of dissolved CO_2 will indicate the presence of separate-phase or dissolved-phase CO_2. The concentration of CO_2 will be used to ascertain whether separate-phase CO_2 may be present, based on accepted mass-transfer relations and equilibrium constants.

10.4.1 Monitoring Wells Above the Confining Zone: Sampling Frequency, Analytical Suites, QA/QC, and Reporting Requirements

10.4.1.1 Mississipian Wells

Gas sampling ports shall be installed in the two existing Mississippian wells shown in Figure 10.1 to collect head gas to detect and measure the amount of early breakthrough or off-pattern migration of CO_2. These two wells will be sampled three times before injection to establish baseline CO_2 concentration. Table 10.7 presents the analytical suite to be monitored and the monitoring frequency for monitoring wells within and above the injection zone. Produced water and casing head gas will be sampled, analyzed, and compared with the baseline survey data to determine the presence of CO_2 and other parameters in the Mississippian reservoir. The inorganic indicator parameters are known to be associated with chemical reactions in the presence of CO_2 and therefore are expected to provide information about the presence of the injectate in the hydrogeologic formations. The sampling and testing will continue every 3 months during the post injection phase.

Table 10.7—Geochemical analytical suite to be monitored in the Mississippian and Upper Wellington (USDW) wells at the Wellington site.

Field Parameters	Pre-Injection	During Injection	Post-Injection
pH	Once a week for 3 weeks	Every 3 months	Every 6 months
Specific Conductivity	Once a week for 3 weeks	Every 3 months	Every 6 months
Temperature	Once a week for 3 weeks	Every 3 months	Every 6 months
Dissolved Oxygen	Once a week for 3 weeks	Every 3 months	Every 6 months
Gas-Water Ratio	Once a week for 3 weeks	Every 3 months	Every 6 months
Depth to Water	Once a week for 3 weeks	Every 3 months	Every 6 months
TDS/Salinity	Once a week for 3 weeks	Every 3 months	Every 6 months
Indicator Parameters			
Alkalinity	Once a week for 3 weeks	Every 3 months	Every 6 months
Bromide	Once a week for 3 weeks	Every 3 months	Every 6 months

Calcium, Iron, Magnesium, Potassium, Dissolved Silica	Once a week for 3 weeks	Every 3 months	Every 6 months
Chloride	Once a week for 3 weeks	Every 3 months	Every 6 months
Sodium	Once a week for 3 weeks	Every 3 months	Every 6 months
Total CO_2	Once a week for 3 weeks	Every 3 months	Every 6 months
Total Fe	Once a week for 3 weeks	Every 3 months	Every 6 months
Total Fe (II)	Once a week for 3 weeks	Every 3 months	Every 6 months
Total NH_4+	Once a week for 3 weeks	Every 3 months	Every 6 months
Total NO_3^{2-}	Once a week for 3 weeks	Every 3 months	Every 6 months
Total SO_4^{2-}	Once a week for 3 weeks	Every 3 months	Every 6 months
Total PO_4^{3-}	Once a week for 3 weeks	Every 3 months	Every 6 months
Total HCO_3^-	Once a week for 3 weeks	Every 3 months	Every 6 months
Total CO_2	Once a week for 3 weeks	Every 3 months	Every 6 months
Concentration of Organics			
DOC	Once a week for 3 weeks	Every 3 months	Every 6 months
TOC	Once a week for 3 weeks	Every 3 months	Every 6 months
DIC	Once a week for 3 weeks	Every 3 months	Every 6 months
Stable Isotopes			
δ18O	Once a week for 3 weeks	Every 3 months	Every 6 months
δD	Once a week for 3 weeks	Every 3 months	Every 6 months
δ13C for Carbonates in System	Once a week for 3 weeks	Every 3 months	Every 6 months

10.4.1.2 Upper Wellington Formation (USDW)

Samples will be collected once a week for 3 weeks before injection. This information will constitute baseline data for future comparison during the injection and post-injection phases. Table 10.7 lists the constituents that are to be tested during the injection phase and the testing frequency. Water-quality parameters will be repeatedly checked for any changes with time for ph, conductivity, alkalinity, DO and redox values. During the post-injection period, the same tests described above for the injection period will be conducted every 6 months. The sampling frequency may be increased if the results of monitoring indicate possible fluid leakage or endangerment of USDWs.

10.4.1.3 Sampling and Analysis Procedures and Quality Asssurance/Quality Control (QA/QC)

The following sampling, handling, and analyses QA/QC procedures will be followed to ensure the acquisition of high-quality data:

- Static water levels in the USDW (Upper Wellington) will be determined using an electronic water level indicator before any purging or sampling activities. Dedicated pumps (e.g., bladder pumps) will be installed in each monitoring well to minimize potential cross contamination between wells and minimize the introduction of atmospheric CO_2.
- Each USDW (Upper Wellington) monitoring well will be purged using a submersible pump. At least three well volumes will be purged before obtaining low-flow samples using a pump. Samples will be dispensed into clean new laboratory-supplied containers and field preserved as required by the analytical method.
- The pumps, tubing, and any other downhole accessories will be rinsed with deionized water and placed in remel Anerobags for travel to the field site. During pump deployment and at other times, care will be taken to ensure that equipment to be used inside the monitoring wells remains clean and does not come in contact with potentially contaminating materials.
- All field and downhole equipment will be properly calibrated according to manufacturer specifications.
- Exposure of the samples to ambient air will be minimized.
- Groundwater pH, temperature, specific conductance, and dissolved oxygen will be monitored in the field using hand-held portable probes.
- For data validation purposes, the following samples will be analyzed with each batch of collected samples:
    - One or two field duplicates, sometimes triplicates, depending on the accuracy of instruments provided to analyse the waters
    - One equipment rinsate

    - One matrix spike (when appropriate for the analytical method)
    - One trip blank
- A chain-of-custody record will be completed and will accompany every sample. All sample bottles will be labeled with durable labels and indelible markings. A unique sample identification number, sampling date, and analyte(s) will be recorded on the sample bottles and sampling records will be written for each well. Sampling records (e.g., a field logbook, individual well sampling sheet) will indicate the sampling personnel, date, time, sample location/well, unique sample identification number, collection procedure, measured field parameters, and additional comments as needed.
- Where appropriate, ASTM Method D6911-03 (2003) will be followed for packaging of samples. Immediately upon sample collection, containers will be placed in an insulated cooler and cooled to 4 degrees Celsius. Upon receipt at the Kansas State laboratory for analysis, the samples will be accepted and tracked by the laboratory from arrival through completed analysis.
- All groundwater quality results will be entered into a database or spreadsheet with periodic data review and analysis.

10.4.1.4 Groundwater Quality Data Reporting

The following information will be submitted to the EPA in all semi-annual monitoring reports:

- The most up-to-date historical database of all groundwater monitoring results,
- Interpretation of any changing trends and evaluation of fluid leakage and migration. This may include graphs of relevant trends and interpretative diagrams,
- A map showing all monitoring wells, indicating those wells that are believed to be in the location of the separate-phase CO_2 plume,
- The date, time, location, and depth of all groundwater samples collected and analyzed,
- Copies of laboratory analytical reports,

- A description of sampling equipment,
- Chain of custody records,
- The name and contact information for the laboratory manager at Kansas State University,
- Identification of data gaps,
- Any changes to the project Testing and Monitoring Plan,
- Presentation, synthesis, and interpretation of the entire historical data set,
- Documentation of the monitoring well construction specifications, sampling procedure, laboratory analytical procedure, and QA/QC standards.

10.5 Carbon Dioxide Plume and Pressure-Front Tracking (§ 146.90 [g])

Identification of the position of the injected CO_2 plume and the presence or absence of elevated pressure (i.e., the pressure front) is integral to protection of USDWs for Class VI projects. Monitoring the movement of the CO_2 and the pressure front is necessary to both identify potential risks to USDWs posed by injection activities and to verify predictions of plume movement to ensure that the plume is adequately confined. Monitoring movement of the plume and the pressure front also provides necessary data for comparison to model predictions and inform re-evaluation of the AoR. Arbuckle monitoring well construction information is presented in Section 10.2. Both direct and indirect measurement methods will be used to monitor the movement of the pressure and plume fronts as discussed in the following sections.

10.5.1 Monitoring Pressure Front (§ 146.90 [g])

The Class VI rule requires that fluid pressure be directly monitored within the injection zone (40 CFR 146.90[g][1]). This type of monitoring provides observations of increases in formation pressures and support tracking the migration of the pressure front (40 CFR 146.90[g][1]).

10.5.1.1 Direct Arbuckle Pressure Monitoring (§ 146.90 [g][1])

Pressure transducers in the injection zone will be installed in the Arbuckle monitoring well KGS 2-28 and in injection well KGS 1-28. The transducers will record pressures continuously every 30 seconds in both the injection and monitoring wells.. The system will have a battery backup or alternative power supply to ensure continued collection of data during power failures. The electronic data from the continuous recorder will be stored on multiple data storage media for redundancy. The data will be backed up on an electronic media storage device. As indicated in Section 13.4, a separate alarm system will monitor surface and bottomhole pressures every 30 seconds in the injection well and trigger a system shutoff and notification to Berexco if a violation of the injection pressure limits specified in Table 13.1 occurs.

Pressure time series at the Arbuckle monitoring and injection wells will be constructed and used to monitor the growth of the pressure front. The pressure data will be compared with a model-based prediction of the pressure front, and if necessary, the simulation model will be recalibrated to conform to field data. The UIC program director will be kept updated of pressure observations via quarterly reporting of the pressure time series and will be consulted during model reevaluation if warranted by the data. Based on modeling results, the pressure in the Arbuckle is expected to stabilize to nearly pre-injection levels within 3 months of cessation of injection. Therefore, the frequency for pressure monitoring will be successively reduced during the post-injection phase based on the observed field conditions. If field conditions warrant a revision of the proposed post-injection monitoring frequency, a revised pressure monitoring plan will be submitted to the EPA for review and comment.

10.5.1.2 Indirect Monitoring of Pressure Front by Surface Displacement (§ 146.90 [g][2])

In addition to direct monitoring, the pressure front will also be tracked by monitoring surface deformation as a result of CO_2 injection using the InSAR approach (Interferometric Synthetic Aperture Radar). This technique will provide an independent means to corroborate the pressure front constructed from direct monitoring of pressures in the Arbuckle injection and monitoring wells. InSAR is a radar technique that measures the phase difference between successive satellite orbits. Tropospheric effects between satellite orbits will be removed using data acquired by the MODIS satellite. Once tropospheric effects are removed, any phase differences between the images will be proportional to small differences in distance between the satellite antenna positions and the ground, which could indicate surface deformation associated with elevated pressures due to CO_2 injection at depth.

Archives of InSAR data will be downloaded before injection to establish a range of baseline surface deformation at the Wellington Field related to seasonal effects (e.g., freeze-thaw cycles and dry vs. wet seasons). During the 9-month injection period and 60 days following injection, InSAR measurements shall be collected approximately every 20 days. After the injection period, data collection and analysis will continue but will decrease incrementally to eventually every 12 months until project closure. The InSAR data can provide a time-series of deformation and subsequent relaxation of the ground surface. The InSAR time-series will establish incremental deformation of the land surface due to CO_2 injection and will be compared with plume dimensions obtained from simulation studies and other direct/indirect monitoring data discussed below.

In addition to InSAR data, Continuous GPS (CGPS) data will also be acquired at cemented platforms for purposes of calibration and verification of the vertical component of the surface displacement field using InSAR. The CGPS data will provide three components of the surface displacement (i.e., northing, easting and vertical) to add tighter constraints to the deformation field detected using InSAR. CGPS data will be downloaded via a laptop on a monthly basis. All data files (24-hour periods) will be recovered for archiving and analysis to enable detection of surface accelerations related to subsurface deformation.

10.5.2 Monitoring the Plume Front

Various direct and indirect MVA tools and techniques will be used to monitor, verify, and account for injected CO_2 in the Arbuckle saline aquifer. The crosswell tomography, U-tube, 3-D seismic, and continuous active source seismic monitoring (CASSM) technology will be used to monitor and visualize the movement of the CO_2 plume. The monitored data will also be used to revise the simulation model, update site characterization, and potentially refine the monitoring plan, if necessary. Each of the plume-monitoring techniques mentioned above, along with the monitoring plan, is discussed below.

10.5.2.1 Direct Geochemical Monitoring of the Plume Front: U-Tube Sampling , (146.90 [g], [i])

Understanding the geochemistry of reservoir gases is critical to understanding how carbon is sequestered in geological formations. The U-tube sampler (Freifeld et al., 2005) is able to collect continuous samples of reservoir fluids near in-situ temperatures and pressures. This innovative apparatus has greatly enhanced the success of CO_2 injection pilot studies at the Frio Brine Pilot, Dayton, Texas; the SECARB Cranfield Test, Cranfield, Mississippi; and the CO2CRC Otway Project, Victoria, Australia (Doughty et. al., 2008; Freifeld, 2009) by significantly improving the quality and quantity of samples that can be collected from deep storage reservoirs during supercritical CO_2 injections. Such sampling is difficult because dissolved gasses and supercritical fluids, which exist at high pressures and temperatures in the reservoir, quickly exsolve or flash to gas as they are brought to the surface for analysis (Freifeld, 2009). The U-tube sampler will be installed in monitoring well KGS 2-28.

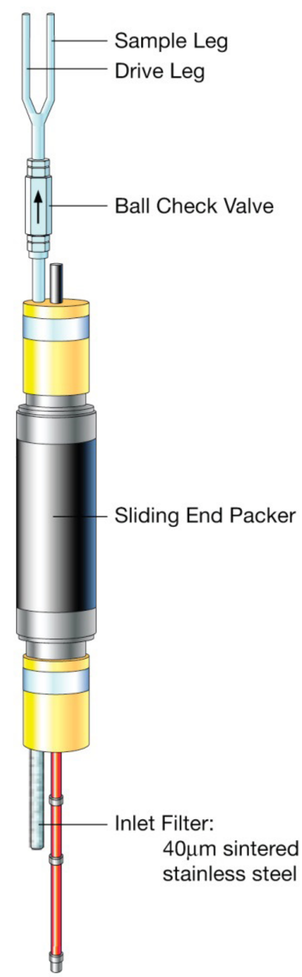

Figure10.4—Schematic of the U-tube sampling device (source: JGR, Freifeld et al, 2005).

The U-tube (Figure 10.4), which is constructed of stainless steel tubing and fixed within the borehole with tubing strings that reach to the surface, will be installed in the Arbuckle observation borehole (KGS 2-28). The perforated interval will be isolated using a packer with feed throughs to accommodate the U-tube sampling system and other permanent instruments. The drive leg of the U-tube is connected to a source of compressed nitrogen and the other attached to a sampling manifold contained in a trailer on site. After first flushing the loop of tubing with N_2 gas, the sample and drive legs will be vented and pressure in the U-tube will decrease, allowing subsurface fluids to enter the sampling inlet due to the pressure differential between the U-tube (atmospheric) and the reservoir. To recover the sample, N_2 gas will again be used on the drive leg to increase the pressure in the tubing, closing the check valve and forcing fluid up to a high pressure sampling cylinder. Inside the cylinder, brine, dissolved gases, and supercritical fluids will be collected at near in-situ conditions, allowing accurate quantification of the relative concentrations of each component.

The U-tube surface sampling instrumentation will consists of a supply of N_2, a high pressure gas booster, and a valve panel to facilitate collection of mixed phase and separate phase subsamples. Samples will be collected on a weekly basis until breakthrough to identify the arrival of the CO_2 plume and co-injected tracers (e.g., sulfur hexafluoride). After breakthrough, samples will be collected initially on an increased sampling frequency and then gradually decreased as geochemical changes slow. Subsamples will be collected and sent to laboratories for analysis of constituents such as pH, EC, alkalinity, cation and anion chemistry, dissolved gases, and isotopic composition as presented in Table 10.7. If hydrocarbons are present in the subsurface, they will be analyzed and may be used in equilibrium thermodynamic models to aid in the estimation of the rate of CO_2 dissolution into the formation brines. Tracer gases including SF_6 (sulfur hexafluoride) and Kr (krypton) shall be periodically co-injected with the CO_2 to facilitate estimation of the travel time between the injection and monitoring wells/boreholes. Approximately 55 kg of SF_6 and 230 ft^3 of Kr 230 will be injected every eight weeks at KGS 1-28.

Table 10.8—Geochemical analytical suite to be monitored in the Arbuckle monitoring well (KGS 2-28) at the Wellington site.

Field Parameters	Pre-Injection	During injection	Post-Injection
pH	Once a week for 3 weeks	Every 45 days	Every 6 months
Specific Conductivity	Once a week for 3 weeks	Every 45 days	Every 6 months
Temperature	Once a week for 3 weeks	Every 45 days	Every 6 months
Dissolved Oxygen	Once a week for 3 weeks	Every 45 days	Every 6 months
Gas-Water Ratio	Once a week for 3 weeks	Every 45 days	Every 6 months
Depth to Water	Once a week for 3 weeks	Every 45 days	Every 6 months
TDS/Salinity	Once a week for 3 weeks	Every 45 days	Every 6 months
Indicator Parameters			
Alkalinity	Once a week for 3 weeks	Every 45 days	Every 6 months
Bromide	Once a week for 3 weeks	Every 45 days	Every 6 months
Calcium, Iron, Magnesium, Potassium, Dissolved Silica	Once a week for 3 weeks	Every 45 days	Every 6 months
Chloride	Once a week for 3 weeks	Every 45 days	Every 6 months
Sodium	Once a week for 3 weeks	Every 45 days	Every 6 months
Total CO_2	Once a week for 3 weeks	Every 45 days	Every 6 months
Total Fe	Once a week for 3 weeks	Every 45 days	Every 6 months
Total Fe (II)	Once a week for 3 weeks	Every 45 days	Every 6 months
Total NH_4+	Once a week for 3 weeks	Every 45 days	Every 6 months
Total NO_{2-3}	Once a week for 3 weeks	Every 45 days	Every 6 months
Total SO_{2-4}	Once a week for 3 weeks	Every 45 days	Every 6 months
Total PO_{3-4}	Once a week for 3 weeks	Every 45 days	Every 6 months
Total HCO_3^-	Once a week for 3 weeks	Every 45 days	Every 6 months
Total CO_2	Once a week for 3 weeks	Every 45 days	Every 6 months
		Every 45 days	
Concentration of Organics		Every 45 days	
DOC	Once a week for 3 weeks	Every 45 days	Every 6 months
TOC	Once a week for 3 weeks	Every 45 days	Every 6 months
DIC	Once a week for 3 weeks	Every 45 days	Every 6 months
Stable Isotopes			
δ18O	Once a week for 3 weeks	Every 45 days	Every 6 months
δD	Once a week for 3 weeks	Every 45 days	Every 6 months
δ13C for Carbonates in System	Once a week for 3 weeks	Every 45 days	Every 6 months

10.5.2.2 Indirect Geochemical Monitoring of the Plume Front: Seismic Surveys (146.90 [g], [i])

Both borehole and surface seismic methods will be used to track the CO_2 plume. Surface seismic data has the advantage of being laterally extensive, but borehole seismic methods (especially crosswell, which will be used at Wellington) produce higher resolution images but at less penetration (distance from transmitting and receiving equipment relative to target) than surface seismic methods because seismic waves pass through weathered surface horizons only once (for surface to borehole) or not at all (for cross well), minimizing attenuation and distortion. The higher resolution provided by the borehole seismic may be useful where the CO_2 plume is predicted to be thin or complex in shape. The seismic plume-tracking techniques and monitoring plans to be employed on the Wellington project are discussed below.

10.5.2.2.1 High Resolution Seismic Survey

A 3D seismic survey has already been acquired and processed as discussed in Section 4.8. This information will provide a baseline to compare with a final 3D seismic acquisition before site closure. The 3D data will be interpreted and compared with the baseline survey to map the final extent of the CO_2 plume to demonstrate containment in support of site closure.

10.5.2.2.2 Cross-Well Seismic Methods

Cross-well seismic methods deploy sources and receivers in several different wells, producing a survey that images the plane between the wells. The equipment is generally deployed in wells not more than 1,500 ft apart (Hoversten et al., 2002). A seismic source is deployed down one well and seismic sensors are deployed down additional wells. Cross-well surveys using several wells are able to generate three-dimensional cross-well surveys (Washbourne and Bube, 1998). The crosswell seismic technique measures velocity and attenuation characteristics to model CO_2 saturations and/or pressure changes during CO_2 injection. As illustrated in Figure 10.5, in continuous monitoring mode, this technique can provide information about how the CO_2 is migrating in the subsurface.

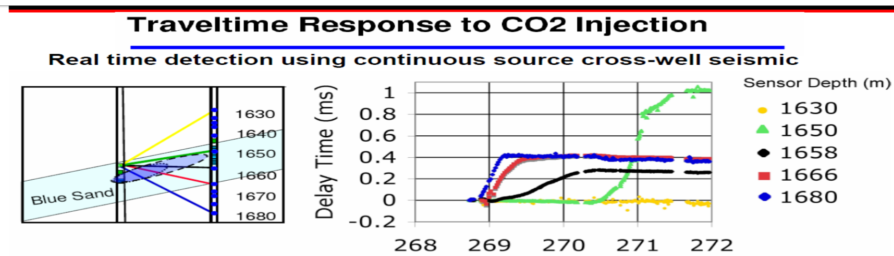

Figure 10.5—Schematic of continuous active-source seismic monitoring (CASSM) Frio-II experiment with conceptual CO_2 plume after one day (inner short dash) and after two days (outer long dash), with measured delay times at three sensor depths over three and a half days of CO_2 injection (right). (Courtesy of Freifeld et al., 2009)

By measuring changes in travel-time and signal amplitude between the wells, tomographic techniques are also used to map velocity and attenuation variations in the section between the wells. These can be used to model CO_2 saturations and/or pressure changes. In addition, cross-hole data can be useful for assessing how effectively the pore space in the storage reservoir is being exploited, which is useful for storage prediction modeling. Because cross-hole seismic uses much higher frequencies than surface seismic (up to 1,000 Hz or more), it interrogates rock and fluid properties at a much finer scale but with much shorter interrogation distances, thereby limiting well separation. Therefore, the method provides valuable ancillary information for the quantitative assessment of surface seismic in proximity to appropriately spaced wells. The technology has been successfully used to capture the CO_2 plume at the Frio experimental storage site in Texas (Figure 10.6). Additional details about the method and its application at the Frio site are documented by Daley et al. (2007) and Freifeld et al. (2009).

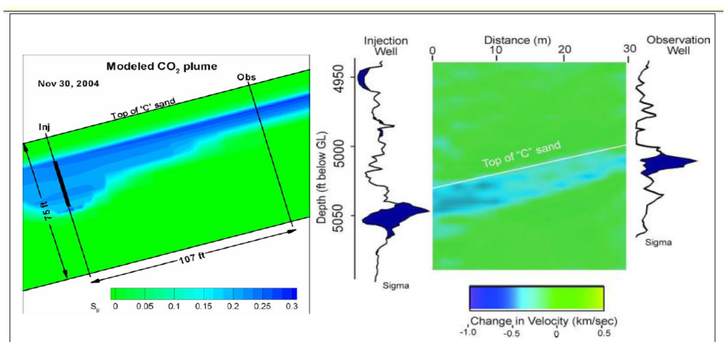

Figure 10.6—Cross-hole seismic imaging at the Frio experimental site in Texas. Velocity tomography (right) compared with reservoir flow simulation (left); (Images courtesy of Tom Daley (Lawrence Berkley National Laboratory); Christine Doughty, LBNL; and Susan Hovorka, University of Texas.

The Arbuckle injection well (KGS 1-28) will be fitted with the continuous active-source seismic monitoring (CASSM) sources that in combination with the CASSM receivers placed in the Arbuckle observation borehole, KGS 2-28, will enable a real-time monitoring of the CO_2 plume front from the injector well. The Piezotube CASSM source, a hollow cylinder, will be installed on production tubing in the annulus of the injection well either above or below the packer (or both). A specially designed source carrier shall be used, acting as a "pup" joint of tubing. The installation will include attaching the cable to power the CASSM source, which will run to the surface. The CASSM receivers will be installed on production tubing in the monitoring borehole (KGS 2-28), along with other monitoring instrumentation (pressure/temperature gauge, U-tube, etc). The CASSM receivers will be an array of hydrophones or similar sensors, with spatial distribution such that the expected vertical extent of the plume is monitored. The CASSM system will provide monitoring along specific source-sensor ray paths, complimenting the full cross-well tomography survey to be acquired separately.

A pre-injection cross-well tomography survey will be carried out before the subsurface seismic velocity field is perturbed by the CO_2 injection and will thus be a baseline for the later surveys and for calculating time-lapse changes. The second cross-well tomography survey will be conducted approximately halfway through the injection to estimate the plume location between the Arbuckle injector and observation boreholes.

The CASSM surveys will be acquired at a temporal resolution on the order of 10-30 minutes, allowing estimation of plume growth in real time, until the instruments are removed for the full cross-well survey. The cross-well survey(s) will be useful as bookends to the CASSM survey, providing a detailed spatial description of the CO_2 distribution and the seismic wave field. This plan will alleviate the shortcoming of the relatively sparse spatial sampling of the CASSM, which leaves uncertainty in some aspects of the interpretation of the seismic waveform and the CO_2 distribution (CASSM focuses on the first arrival only, while cross-well allows understanding of later arriving phases and provides imaging in the entire 2D plane between wells).

10.6 Reporting of Monitoring Results to EPA (§ 146.91)

Results of monitoring activities will be submitted to the EPA according to the schedule defined below. Data will be submitted in electronic form directly to the EPA's geologic storage database, where they can then be accessed by the UIC program director.

Prior-to-Injection Report

- CO_2 stream analyses
- Descriptive report of initial MIT as per 40 CFR 146.91(e)
- Baseline InSAR data
- Groundwater geochemistry analyses of USDW
- Groundwater geochemistry analyses of Mississippian formation
- Background U-tube geochemistry

Semi-Annual Report

- Quarterly CO_2 stream characteristics (physical, chemical, other) detailing the list of chemicals analyzed, a description of the sampling methodology and the name of the certified laboratory performing analysis, sample dates and times, and interpretation of the results with respect to regulatory requirements and past results. Any changes to the physical, chemical, and other relevant characteristics of the carbon dioxide stream from the proposed operating data also will be documented
- Description of any event(s) that exceeded operating parameters for annular pressure or injection pressure and corresponding action
- Description of any event(s) that triggered a shut-off device and the corresponding response undertaken
- Monthly volume and/or mass of CO_2 injected over the reporting period;
- Cumulative volume of CO_2 injected over the project life
- Monthly annulus fluid volume added to the injection well

- If pressure or flow rate exceeded permit limits during the reporting period, an explanation of the event(s), including the cause of the excursion, the length of the excursion, and response to the excursion
- Identification of data gaps, if any
- Any necessary changes to the project Testing and Monitoring Plan to continue protection of USDWs
- Continuous measurement of flow rate and pressure in injection well, including the following:
    - Tabular data of all flow-rate measurements
    - Monthly average, maximum, and minimum value for flow rate and volume, injection pressure, and annular pressure
    - Total volume (mass) injected each month
    - Cumulative volume (mass) for the project
    - Demonstration of gauge calibration according to manufacturer specifications
- MIT results
- Corrosion monitoring information, including a description of the techniques used for corrosion monitoring, measurement of mass and thickness loss from corrosion coupons, and a calculated corrosion rate
- Bottomhole pressure results in all monitoring wells, including a synthesis and interpretation of the entire historical data set
- InSAR data
- Groundwater geochemistry sampling results and analyses of USDW
- Groundwater geochemistry sampling results and analyses of Mississippian Formation
- U-tube geochemistry results and analyses
- CASSM results
- Seismic results and analyses

Results to be reported within 30 days of event occurrence

- Results of periodic external MITs as per 40 CFR 146.91(b)
- Any well work performed
- Any test of the injection well as required by the EPA
- If conducted, pressure fall-off test results, including raw data collected during the fall-off test in a tabular format, measured injection rates and pressures, demonstration of gauge calibration according to manufacturer specifications, diagnostic curves of test results, noting any flow regimes, description of quantitative analysis of pressure-test results, calculated parameter values from analysis, including transmissivity and skin factor.

Information to be reported within 24 hours of occurrence

- Any evidence that the CO_2 stream or associated pressure front has or may cause endangerment to a USDW
- Any non-compliance with permit condition(s), or malfunction of the injection system, that may cause fluid migration to a USDW
- Any triggering of a shut-off system, either downhole or on the surface
- Any failure to maintain mechanical integrity
- Any release of CO_2 to the atmosphere
- A description of any event that exceeds operating parameters for annulus pressure or injection pressure

30 Days Notification

- Any well workover, or testing in compliance with EPA directives
- Any well stimulation activities, other than stimulation for formation testing at the injection well as described in Section 8.13
- Any other injection well testing

10.7 Periodic Review of Monitoring Plan (§ 146.90 [j])

The testing and monitoring plan will be periodically reviewed to incorporate a) monitoring data, b) operational data, and c) the most recent AoR re-evaluation. Specifically, a review will be conducted if there is:

- model revision that affects the predicted movement of the plume and pressure fronts (ie, size and shape of AoR)
- evidence of leaching/mobilization of metals or organic constituents in the subsurface that may indicate a need to modify groundwater monitoring parameters or analyses
- operational parameters outside the range specified in Section 10.3.2.5
- AoR re-evaluation
- well construction, mechanical integrity, and corrosion testing data indicating a need to modify the well testing regime, e.g., by revising MITs or corrosion monitoring activities.
- five years elapsed since commencement of injection and site closure has not occurred,

The outcome of the review may be an amended testing and monitoring plan, which will be submitted to the EPA director for approval. If an amended plan is not required, then a justification for the same in the form of a report will be submitted to the EPA director for approval. The amended plans or demonstrations that no amendment is required shall be submitted to the director for approval as follows:

(1) Within one year of an AoR re-evaluation;

(2) After any significant changes to the facility, such as addition of monitoring wells or newly permitted injection wells within the AoR, on a schedule determined by the EPA director; or

(3) When required by the director.

10.8 Period of Data Retention (§ 146.91 [f])

<u>All data</u> collected in support of this Class VI application (including background geologic/ hydrogeologic data and analyses, geophysical logs, modeling results, well design and plugging in-

formation/reports) as well as all operating information (including all testing/monitoring activities documented in Sections 10.2–10.7, AoR re-evaluation, corrective action records, post-injection data, well plugging report, and site closure records including data and information used in support of the alternative site care time frame) will be retained for at least 10 years after site closure.

Berexco understands that the EPA director has authority to require that all project records described above (and any additional requetsted information) be retained for longer than 10 years after site closure. Additionally, upon request, Berexco will deliver all project records to the EPA program director.

10.9 Quality Assurance Plan [§ 146.90 (k)]

All Quality Assurance and Quality Control (QA/QC) measures will be documented in semi-annual MVA reports and all intermediate reports that contain field data will be submitted to the EPA.

Data obtained from externally contracted laboratories—such as for CO_2 stream analyses, water-quality testing, temperature/geophysical logs, and corrosion data—will be accompanied with the QA/QC protocol and results followed by the respective laboratories.

Section 10.3.1.4 documents the Quality Assurance/Quality Control procedures to be followed for obtaining and handling CO_2 source samples. QA/QC procedures to be followed during acquisition of groundwater quality data above the injection zone are documented in Sections 10.4.1.3. As discussed in Section 10.5.1.2, the continuous GPS station will be used to calibrate and verify the InSAR satellite data. Instruments installed locally, such as pressure transducers and flow meters, will be calibrated according to the manufacturer's recommendations, and the procedure and results will be documented in reports submitted to the EPA.