BELL CREEK TEST SITE – MONITORING EXPERIMENTAL DESIGN PACKAGE

Plains CO_2 Reduction (PCOR) Partnership Phase III
Task 5 – Deliverable D43

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INTRODUCTION

The Plains CO_2 Reduction (PCOR) Partnership, led by the Energy & Environmental Research Center (EERC), is working with Denbury Onshore, LLC (Denbury) to determine the effect of a large-scale injection of carbon dioxide (CO_2) into a deep clastic reservoir for the purpose of simultaneous CO_2 enhanced oil recovery (EOR) and the incidental CO_2 storage that will occur at the Bell Creek oil field, which is operated by Denbury.

There is growing recognition that EOR operations utilizing CO_2 as the injectant can have additional value for the public and the environment by taking advantage of the normal situation that commonly takes place in any EOR operation utilizing an outside substance to increase oil production from a reservoir. The fluid being injected, including saltwater when utilized in a secondary recovery project, ultimately occupies some of the pore space vacated by the produced oil. At the time of depletion and the closure of the EOR project, the injectant remains stored for eternity. This project is directed at taking advantage of the opportunity to monitor and account for this incidental storage of CO_2 that occurs during normal oilfield operations.

A technical team that includes Denbury, the EERC, and others conducted a variety of activities to determine the baseline reservoir characteristics including predictive simulations of the CO_2 injection, guide monitoring strategies, determine the ultimate fate of injected CO_2, and facilitate assessment of various potential injection schemes. Denbury will carry out the injection and production operations, while the EERC will provide support for the site characterization, modeling and simulation, and integrated risk assessment and will aid in the development of the monitoring, verification, and accounting (MVA) plan to address key technical subsurface risks of the incidental CO_2 storage associated with EOR. The Bell Creek demonstration project is a unique opportunity to develop a set of cost-effective MVA protocols for large-scale (>1 million tons per year) combined CO_2 EOR and storage in a clastic formation. The baseline MVA work also provides valuable data to support the design and implementation of an injection/production scheme for large-scale CO_2 EOR and its incremental storage.

The field demonstration test conducted in the Bell Creek area of Powder River County, Montana, will evaluate the field's potential for CO_2 EOR and CO_2 storage. The CO_2 will be obtained from the Lost Cabin gas-processing plant in Fremont County, Wyoming, and injected into a sandstone reservoir in the Lower Cretaceous Muddy (Newcastle) Formation at a depth of approximately 4500 feet (1372 meters). The Lost Cabin Gas Plant is operated by ConocoPhillips. The plant currently will deliver approximately 50 million cubic feet of CO_2 per day to the Bell Creek oil field (Figure 1). The activities at Bell Creek will inject an estimated 1.1 million tons of CO_2 annually, much of which will be permanently stored in association with the EOR operation.

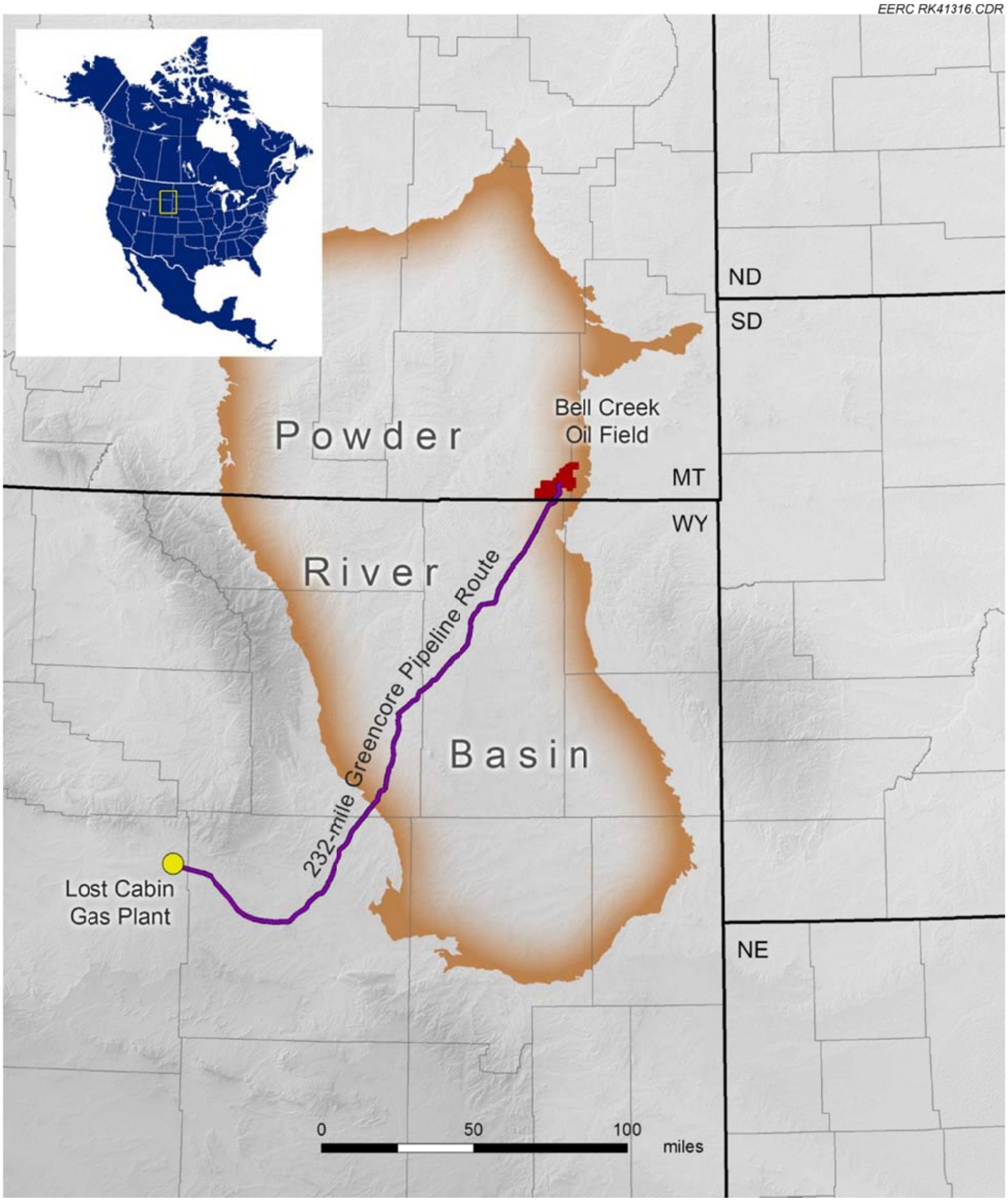

Figure 1. Location of the Lost Cabin Gas Plant and Bell Creek oil field in Wyoming and Montana (modified from Gorecki and others, 2012).

BACKGROUND

The U.S. Department of Energy's (DOE's) goals for carbon capture and storage (CCS) research revolve around developing geologic and terrestrial storage approaches and applying technologies to store significant quantities of CO_2 safely, permanently, and economically. Several means for geological storage of CO_2 are available, including depleted oil and gas reservoirs, deep brine-saturated formations, CO_2 flood EOR operations, and enhanced coalbed methane recovery. DOE is pursuing a vigorous program for demonstration of CCS technology through its Regional Carbon Sequestration Partnership (RCSP) Program, which entered Phase III in October 2007. This phase is planned for a duration of ten U.S. federal fiscal years (October 2007 to September 2017), and its main focus is the characterization and monitoring of large-scale CO_2 injection into geologic formations at CCS sites. Regional characterization activities conducted by the PCOR Partnership indicate that oil reservoirs represent significant opportunities in North America for both long-term storage of CO_2 and incremental oil production through EOR (Peck and others, 2007). The opportunity to cost-effectively store CO_2 while simultaneously producing incremental oil, as a value-added product, provides the basis for conducting the Bell Creek EOR and CCS project as part of the PCOR Partnership's Phase III program.

The PCOR Partnership, covering nine U.S. states and four Canadian provinces, is assessing the technical and economic feasibility of capturing and storing CO_2 emissions from stationary sources in the central interior of North America. The PCOR Partnership's goal is to identify and test CCS opportunities in the central interior of North America. The partnership comprises numerous private and public sector groups from the nine states and four provinces, among them Denbury. The 10-year Phase III program proposed by the PCOR Partnership aims to demonstrate the efficacy of large-scale CO_2 storage coupled with commercial EOR operations at the Bell Creek location. It is anticipated that the results generated at the Bell Creek site will provide insight and knowledge that can be directly and readily applied to similar projects throughout the world. The Bell Creek oil field is one of many oil and gas reservoirs in the PCOR Partnership region that has the potential to store significant amounts of CO_2. Initial estimates suggest that approximately 14 million tons of CO_2 may be stored in the Bell Creek oil field as a result of EOR activities (Botnen and others, 2011). The results of the proposed Phase III test will be broadly applicable throughout the PCOR Partnership region:

- Ten of the 13 state/provincial jurisdictions in the region have oil fields within their boundaries (Sorensen and others, 2011).

- Regional characterization activities conducted under Phases I and II of the PCOR Partnership show that there are hundreds of oil fields in the region that may be suitable for CO_2-based EOR operations (Sorensen and others, 2011).

- Phase I results indicate that in the PCOR Partnership region at least 3.5 billion tons of CO_2 is needed to produce the incremental oil in the fields that were identified as being suitable for CO_2-based EOR (Sorensen and others, 2011).

- Oil fields generally offer the best opportunities to implement large-scale CO_2 storage projects in a timely manner because they are generally much better characterized than saline formations; are already legally established for the purpose of safe, large-scale manipulation of subsurface fluids; and offer a means to offset the considerable costs of CO_2 capture and transportation through the sale of incrementally produced oil (Sorensen and others, 2011).

Developing cost-effective approaches to predict and determine the fate of the injected CO_2 is an important aspect of implementing large-scale CCS technology. Baseline characterization and MVA activities are critical components of geological CCS projects for two key reasons. First, the public must be assured that CO_2 geological storage is a safe operation. Second, to facilitate the establishment and trading of carbon credits, markets need assurance that credits are properly assigned, traded, and accounted for or account for CO_2 stored to meet regulatory requirements. At the Bell Creek Field, the PCOR Partnership will establish baseline conditions through the use of integrated programs that combine robust geological, hydrogeological, geochemical, and geomechanical characterization activities. A cost-effective MVA plan will then be developed based upon the detailed data derived from the geological characterization activities guided by risk. The baseline conditions will also provide a point of comparison to document the movement and fate of the injected gas stream and detect potential vertical and lateral migration from the storage unit. The baseline MVA data will also be used to support the design of the CO_2 injection and oil production scheme for the Bell Creek project.

Demonstrating the technical and economic viability of implementing cost-effective, risk-based MVA strategies at a large-scale (>1 million tons of CO_2 per year) commercial CO_2 EOR project such as the Phase III Bell Creek project will provide stakeholders with the real-world data necessary to move CCS technology deployment forward. The results generated by the Bell Creek project will provide stakeholders, including policy makers, regulators, industry, financiers, and the public, with the knowledge necessary to make informed decisions regarding the real cost and effectiveness of CCS (through CO_2 EOR) as a carbon management strategy.

PCOR PARTNERSHIP PROJECT OBJECTIVES

From the perspective of CCS, the primary project objectives are to demonstrate that 1) CO_2 storage can be safely and permanently achieved on a commercial scale in conjunction with an EOR operation, 2) oil-bearing sandstone formations are viable sinks for CO_2, 3) MVA methods can be established to effectively monitor commercial-scale EOR CO_2 storage projects and to provide a technical framework for the monetization of carbon credits, and 4) the lessons learned and best practices employed will provide the data, information, and knowledge needed to develop similar CO_2 EOR storage projects across the region. A thorough understanding of the monitoring characteristics of the Bell Creek oil field and its surrounding area is necessary to achieve these objectives.

With respect to CO_2 EOR, an objective of the PCOR Partnership at Bell Creek is to understand the nature of the dynamic relationships existing between EOR and CCS, in part, by integrating MVA activities into a commercial EOR project. Targeted MVA data acquisitions will be utilized to enhance and supplement data originating from the commercial EOR project, enhancing overall understanding of incidental storage as it relates to commercial scale EOR operations. Lessons learned from this study can be applied to future CCS projects, allowing operators to make informed decisions regarding monitoring and performance of CO_2 storage projects.

MVA PHILOSOPHY

The PCOR Partnership has developed an approach that integrates site characterization, modeling and simulation, risk assessment, and MVA into an iterative process to produce meaningful results for large-scale CO_2 storage projects (Figure 2). The reservoir-monitoring program will utilize a preinjection (baseline) data set and a staged-injection monitoring approach to allow for time-lapse data acquisition during key intervals of the EOR operation. The surface-, near-surface-, and deep subsurface-monitoring programs are designed to have minimal impact on the commercial operations, supplement available commercial EOR data sets, and address the challenges of limited wellbore access, key risks identified to the project, and reservoir complexities experienced during an active large-scale EOR project. Monitoring data acquisitions are designed to effectively monitor and evaluate CO_2 injection and storage associated with commercial-scale projects.

The MVA activities for this project can be broken down into two groups: 1) surface and shallow subsurface monitoring and 2) reservoir and deep subsurface monitoring. This activity outlines the methods by which the EERC monitored soil gas, surface water, and shallow groundwater to establish baseline conditions throughout the Bell Creek oil field area. Additionally, subsurface and reservoir-centered data sets were acquired to establish baseline conditions and will be used to track both CO_2 and fluid migration during the injection and postinjection (operational) process.

GEOLOGY OF THE BELL CREEK AREA

The Bell Creek oil field in southeastern Montana is an initially subnormally pressured reservoir with significant hydrocarbon accumulation that lies near the northeastern corner of the Powder River Basin (Figure 1). Exploration and production activities for mineral and energy resources in the area over the last 55 years have yielded a significant amount of information about the geology of southeastern Montana and the northern Powder River Basin. Over the course of decades, oil and gas production through primary and secondary recovery (waterflood and polymer flood pilot tests) has resulted in reservoir decline and has now led to the planned implementation of a CO_2 injection-based tertiary oil recovery project. CO_2 will be delivered to the site via pipeline from the Lost Cabin gas plant, where it is separated from the process stream during refinement of natural gas. The plant is located in Fremont County, Wyoming (Figure 2). It will deliver around 50 million cubic feet of CO_2 per day to the Bell Creek oil field.

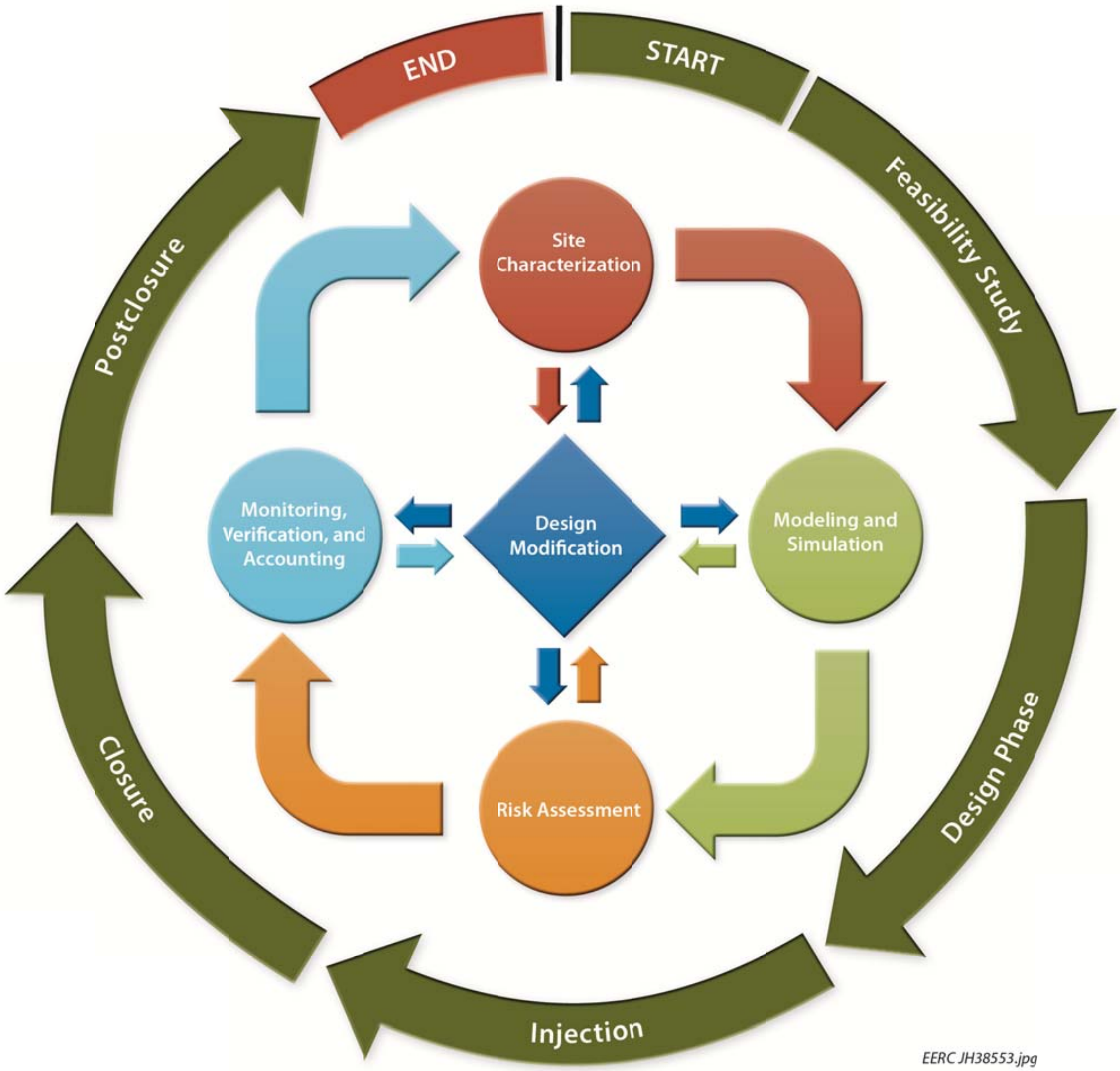

Figure 2. Project elements of the Bell Creek study. Each of these elements feeds into another, iteratively improving results and data interpretation (Gorecki and others, 2012).

CO_2 will be injected into the oil-bearing sandstone reservoir in the Lower Cretaceous Muddy (Newcastle) Formation at a depth of approximately 4500 feet (1372 meters). CO_2 injection will occur in a staged approach (nine planned CO_2 development phases, designated as Phases 1 to 9) across the field (Figure 3). It is expected that the reservoir will be suitable for miscible flooding conditions with an incremental oil production target of over 30 million barrels. The activities at the Bell Creek oil field will inject an estimated 1.1 million tons of CO_2 annually, much of which will be permanently stored at the end of the EOR project.

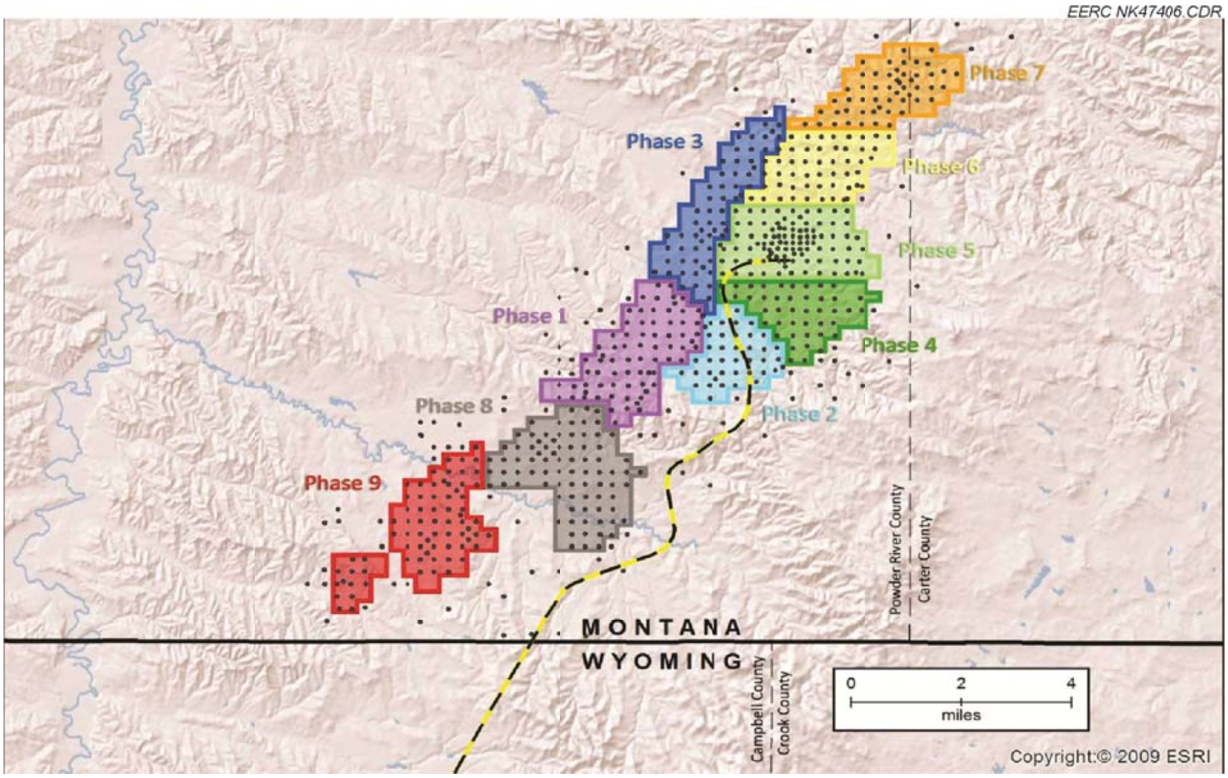

Figure 3. Bell Creek phased CO_2 EOR injection.

Within the Bell Creek oil field, the Muddy Formation is dominated by high-porosity (25%–35%), high-permeability (150–1175 mD) sandstones deposited in a near-shore marine environment (Encore Acquisition Company, 2009). The initial reservoir pressure was 1200 psi, which is significantly lower than the regional hydrostatic pressure regime (2100 psi at 4500 ft) (Saini and others, 2012). The existence of a stable, underpressured system in the Bell Creek Field provides additional support for the suitability of the reservoir as a CO_2 storage reservoir. It demonstrates that both the overlying and underlying sealing formations are competent and capable of maintaining a sustained pressure differential. The oil field is located structurally on a shallow monocline with a 1–2° dip to the northwest and with an axis trending southwest to northeast for a distance of approximately 20 miles. Stratigraphically, the Muddy Formation regionally features an updip facies change from sand to shale that serves as a trap. The barrier bar sand bodies of the Muddy Formation strike southwest to northeast and are overlain by a deltaic siltstone that strikes perpendicularly to the Muddy Formation and finally is partially dissected and somewhat compartmentalized by intersecting shale-filled incisive erosional channels.

The overlying Lower Cretaceous Mowry Formation shale will provide the primary seal, preventing fluid migration to overlying aquifers and to the surface. On top of the Mowry Formation are several thousand feet of low-permeability shale formations, including the Belle Fourche, Greenhorn, Niobrara, and Pierre shales, which will provide redundant layers of protection in the unlikely event that the primary seal fails to prevent upward fluid migrations fieldwide (Figure 4).

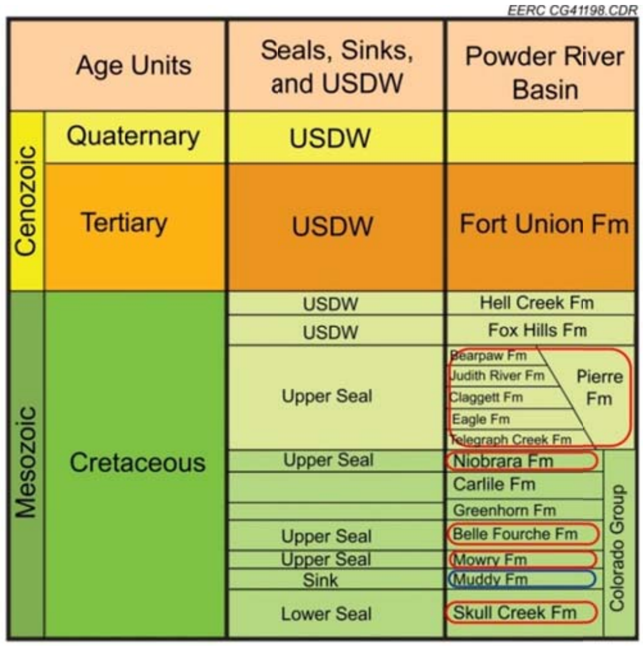

Figure 4. Late Cretaceous to Quaternary stratigraphic column of the Powder River Basin. Sealing formations are circled in red, and the primary oil-producing and sink formation is circled in blue. Formations bearing underground sources of drinking water (USDW) are also identified.

MONITORING SCHEME

The goal of the MVA program is to provide critical data to verify site security; evaluate reservoir behavior during the injection program; determine interactions between oil, water, and CO_2 within the reservoir; determine the ultimate fate of injected CO_2; and investigate mechanisms that affect CO_2 storage efficiency within the EOR process. The MVA program utilizes targeted time-lapse data acquisitions as part of a surface-, near-surface-, and deep subsurface-monitoring program guided by key subsurface technical risk and predictive simulation. If the MVA program identifies a significant variance from anticipated performance, a targeted characterization effort could then be deployed to evaluate the impact and source of the event (Hamling and others, 2012).

The PCOR Partnership strives for the development of sustainable MVA strategies that are compatible with commercial operations and practices (i.e., demonstrate value to commercial operations while integrating EOR operational data into the MVA program with minimal impact for commercial EOR operators) while also being site-specific, cost-effective, and technically viable. The results of the Bell Creek study will provide valuable information and lessons learned regarding technologies suited to future commercial-scale CCS operations so that commercial projects can make informed decisions regarding operations and monitoring strategies.

No single technology exists that is capable of monitoring all areas of interest in a CO_2 storage system from the reservoir level through the surface environment. For this reason, the PCOR Partnership has designed a monitoring program specific to the needs of the Bell Creek

Field which monitors a variety of physical phenomena within the field utilizing a variety of commercially viable technologies and techniques. The suite of technologies is focused on a two-pronged approach that prioritizes monitoring at the reservoir depth and the near-surface environment (Figure 5). Each of these technologies satisfies a specific monitoring need within the field and operates over a unique effective range. However, the specific technologies selected are also designed to operate in a complementary manner where an anomalous signal from one monitoring technique can be investigated through the use of one or more of the remaining techniques. Additionally, the PCOR Partnership is also evaluating the scientific validity and cost-effectiveness of each of these monitoring technologies in order to provide DOE with recommendations on how these technologies may be deployed at other CO_2 storage sites in the future.

Near-Surface-Monitoring Techniques

A robust baseline soil gas- and water-sampling program allowed for scientific assessment of naturally occurring CO_2 and chemical components in the near-surface environment within and near injection activities. The purpose of the near-surface-monitoring program is twofold: 1) to establish baseline conditions for naturally occurring CO_2 levels present in surface water, soil, and shallow groundwater aquifers in the vicinity of the carbon storage formation and 2) to provide a source of data to show that surface environments remain unaffected by potential fluid or gas migration and to identify the source and quantify the impact of an out-of-zone migration event should it occur.

The near-surface-monitoring plan comprises three parts: sampling of soil gas concentrations in the vadose zone, sampling of surface water features, and sampling of shallow groundwater aquifers. Sampling these three zones established a baseline concentration of CO_2 across the range of microenvironments present throughout the Bell Creek oil field. Data acquired can later be used to determine if a CO_2 concentration found in these mediums during operation is a result of natural processes (is within a probable statistical range of naturally occurring levels as determined by baseline data) or may be the result of an out-of-zone fluid migration. If CO_2 or fluid were to migrate from the deep subsurface, they could affect all of these environments or any one independently, depending on the geology and geography of the near-surface environment and the environmental conditions at that time (i.e., season of year, groundwater levels, etc.).

In the event of an environmental impact claim, the near-surface MVA program will provide valuable scientific baseline data to either dispute the claim or provide a means of identifying the source or mechanism of the impact for remediation and subsequently quantify the impact. Monitoring will be carried out on a periodic basis during CO_2 injection to ensure that any migration event can be identified, evaluated, and remediated in a timely manner, minimizing the environmental impact.

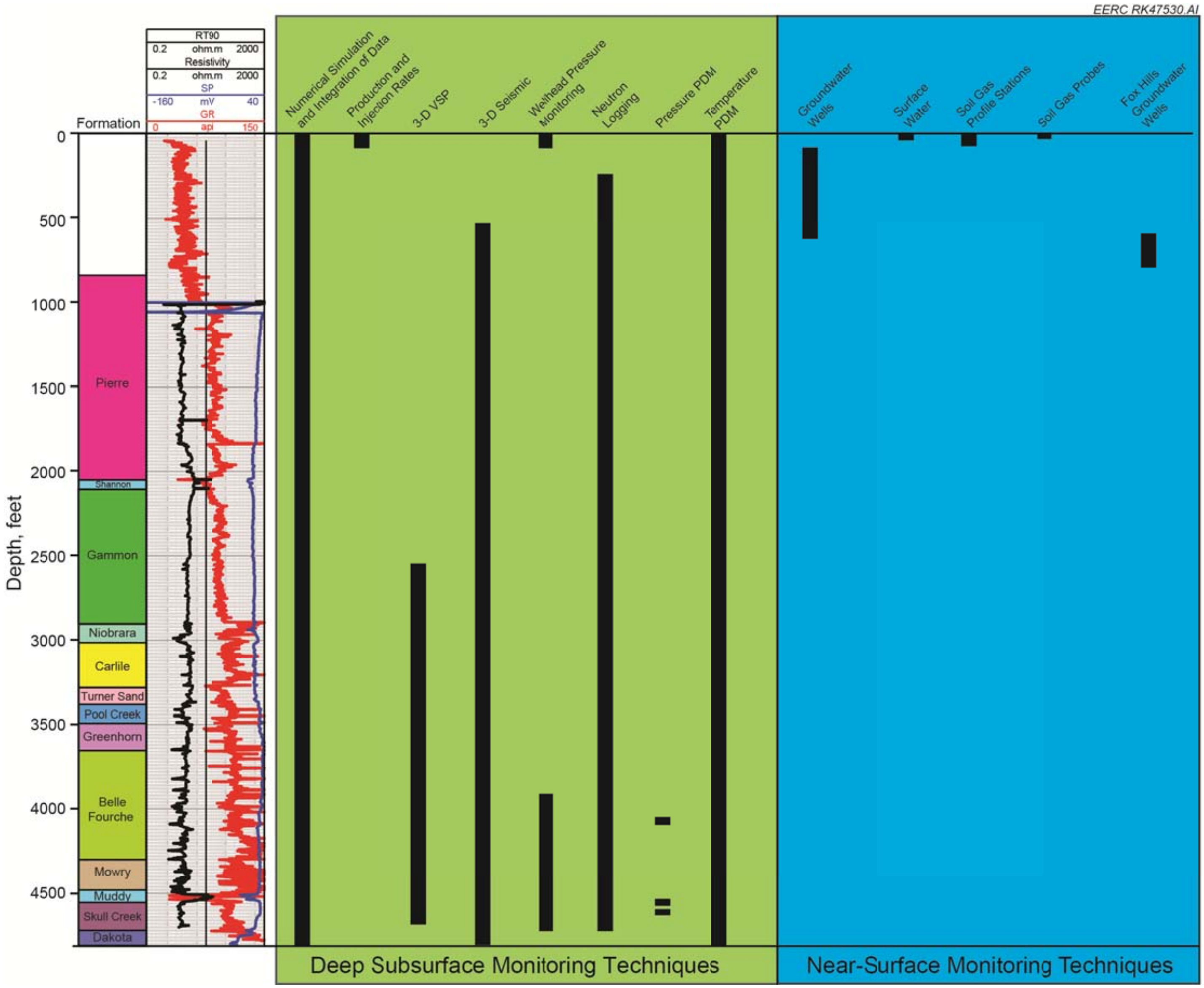

Figure 5. Current and ongoing surface-, near-surface-, and deep subsurface-monitoring techniques employed throughout the Bell Creek oil field and their effective monitoring range as deployed for Bell Creek.

The EERC collected baseline soil gas, groundwater, and surface water samples fieldwide to cover seasonal variation, which began in November 2011 and was completed in April 2013 (Table 1). Statistical analysis was performed on the baseline sampling events to identify spatial and seasonal variation among sample media. Injection will begin in May 2013; once injection begins, groundwater, surface water, and soil gas will be sampled annually in the operational phase (during the summer/fall months to take advantage of optimal site access).

Soil Gas

Vadose zone soil gas monitoring is used to directly measure characteristics of the soil atmosphere that are indirect indicators of processes occurring in and below a sampling horizon. Soil gas monitoring at the Bell Creek Field was accomplished through the use of quarterly sampling via hand-driven probes and the monitoring of fixed soil gas profile stations (SGPSs). The fixed SGPSs were installed within the Phase 1 area and are capable of recovering samples from deeper in the soil profile than the hand-driven probes.

Quarterly fieldwide soil gas sampling, using ASTM International (ASTM) standard procedures, is completed using a hand-driven probe. This method was chosen because of its cost-effectiveness, its low-impact nature mobility (site access), and the fact that a large number of samples can be collected in a short amount of time. The objective is to establish baseline values for several specific gaseous components naturally found in shallow soils. These components include hydrogen (H_2), oxygen (O_2), nitrogen (N_2), carbon monoxide (CO), CO_2, methane (CH_4), ethane (C_2H_6), and ethylene (C_2H_4) as well as isotopic signatures of CO_2 and CH_4. A sudden change in one or any combination of these components during operation could be indicative of an out-of-zone fluid migration or be the result of natural biologic respiration in the soil or other nonrelated phenomenon. If an anomaly is detected, these data can be analyzed to determine the source of the anomaly (biogenic, fluid migration, change in agricultural practices, etc.).

Soil gas sampling consists of extracting representative samples of the gases present within the vadose zone, which includes naturally occurring CO_2. Seasonal variations can dramatically impact the concentration of CO_2 in the vadose zone. Seasonal gas flux in near-surface soils is

Table 1. Anticipated Bell Creek Near-Surface Monitoring Schedule for Fieldwide Soil Gas and Water Sampling

	Sample Date	Completed
Baseline Events	November 2011	X
	April 2012	X
	June 2012	X
	August 2012	X
	November 2012	X
	April 2013	X
Operational Events	Q3 2013	
	Q3 2014	
	Q3 2015	

typically caused by biologic processes, plant roots, and as part of the soil-weathering process. Levels of CO_2 in the vadose zone are typically highest during the summer and lowest during the winter season. The ratio of the stable carbon isotopes that make up the CO_2 may also vary with the seasons. Baseline sampling and analysis were repeated quarterly from November 2011 to April 2013 to capture these variations, and they will be repeated annually (Table 2) during the operational phase (2013–2015).

Fieldwide Soil Gas Probe Monitoring

Soil gas-sampling sites were established at 186 locations across the Bell Creek Field, with emphasis on the Phase 1 area, and at select locations (six to eight well locations per phase unit) throughout the remainder of the field. These locations were chosen because of pad access and the equal spacing (grid) throughout the field. Exact sample locations were identified on-site to avoid any utilities that might be present. Soil gas samples were collected adjacent to well pads at injection/production (active) well sites at 124 locations and at locations near 52 plugged and abandoned (P&A) wells (Figure 6). A three-spot sample pattern was established over each of the P&A locations (100-foot spacing), because these wells could provide a greater potential pathway for out-of-zone fluid migration. In addition to samples collected adjacent to existing well pads, ten samples were collected at select locations between wells (“interspaced” locations) within the Phase 1 area. These sample locations were chosen to provide baseline data at locations not directly associated with wells. The interspaced samples were used as control points and sampled during each event. Sampling occurred adjacent to the EERC monitoring well, 05-06 OW (drilled in December 2011), for the near-surface baseline monitoring program. Samples were established in a three-spot pattern, similarly to the P&A wells, with one direction being counted as an interspaced sample.

All soil gas-sampling locations were identified and marked using a Trimble Nomad G series global positioning system. A utility locate was performed prior to the advancement of the soil gas probes. Sample collection procedures followed guidance outlined in ASTM D5314 (2006). A stainless steel rod with a retractable tip was driven into the ground (either with a slide hammer or electric rotary hammer) to a depth of approximately 3 feet. The rod was then retracted to expose an integrated mesh screen; Teflon tubing was attached to the end of the sample probe, and a vacuum chamber was used to purge the rod content before sample collection. A minimum of three probe casing volumes were removed prior to sampling. A soil gas sample was then collected at each location and analyzed for CO_2, total volatile organic compounds (VOCs), hydrogen sulfide (H_2S), and O_2 using a RAE System PGM-54 handheld multigas meter.

Samples were also collected in Tedlar® bags, labeled with the appropriate sample number, and transported to the EERC field laboratory for analysis. The EERC field laboratory uses the latest generation (Micro Quad 490) of Agilent Technologies refinery gas analyzer gas chromatograph (GC). For confirmatory analysis of the Micro Quad 490 GC, one randomly selected sample out of every 20 collected samples was analyzed by a different technician utilizing an Agilent Technologies RGA-GC 7890A GC with independent calibrations at the EERC laboratory in Grand Forks, North Dakota.

Table 2. Soil Gas-Monitoring Overview for the Bell Creek EOR CO_2 Storage Site MVA Program[1]

Monitoring Technique	Number of Locations	Frequency (baseline)	Frequency (operational)	Measurement
Soil Gas Probe	− 124 active wells − 52 P&A wells − Ten interspaced (between active wells) locations − 05-06 OW	Quarterly, with near-monthly sampling at select sites	Annually, with near-monthly sampling at select sites	*Field* • RAE System PGM-54 handheld multigas meter: CO_2, total VOCs, O_2, and H_2S • Agilent Technologies 490 Micro Quad field GC: CO_2, O_2, N_2, H_2, H_2S, CH_4, CO, C_2H_6, C_2H_4, and carbonyl sulfide (COS) *Laboratory* • Agilent Technologies RGA-GC 7890A lab GC (confirmatory analysis on field GC): CO_2, O_2, N_2, helium (He), H_2, CH_4, CO, C_2H_6, C_2H_4, and additional VOCs • Isotopes (soil gas probe sampling adjacent to select well pads only): ^{2}H (deuterium), ^{3}H (tritium), ^{13}C (carbon-13), ^{14}C (carbon-14), and ^{18}O (oxygen-18)
SGPS	Ten locations, each with three depth intervals: − 3.5 feet − 9.0 feet − 14 feet	Near-monthly, starting October 2012	Near-monthly	

[1] Modified from *Bell Creek Enhanced Oil Recovery –Carbon Dioxide Storage Site Risk-Based Monitoring, Verification, and Accounting Review* Draft Report.

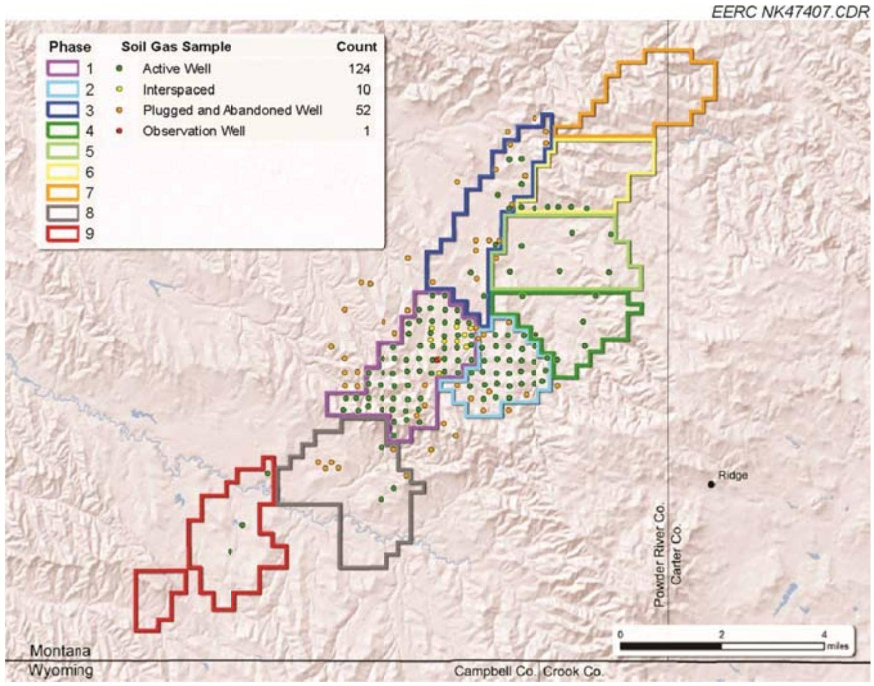

Figure 6. Soil gas probe monitoring locations for each sample type.

SGPS Monitoring

In addition to the soil gas measurements adjacent to the active wells, P&A wells, interspaced locations, and the 05-06 OW monitoring well, ten fixed SGPSs were installed in the Phase 1 area of the Bell Creek site in October 2012 to provide an understanding of how the concentrations of soil gases vary with depth (Figure 7).

Nine of the ten SGPSs were installed near existing active wells, and the other SGPS was installed near the EERC monitoring well, 05-06 OW (Figure 8). Each SGPS consists of a shallow PVC (polyvinyl chloride) well with nested tubing individually screened at depths of 3.5, 9.0, and 14 feet below the ground surface. Each of the screened areas was packed with sand and sealed above and below with a layer of bentonite. The design allows an operator to readily collect and analyze soil gas samples at each depth interval year round, provided that climate conditions allow for site access. The SGPSs were first sampled after installation in October 2012, with plans to sample monthly thereafter. Field and laboratory analyses are conducted similarly to the soil gas probe monitoring program.

Water

Surface water and groundwater sampling is used to measure chemical and hydrologic characteristics in water at the ground surface and belowground. The objective is to establish baseline values for several constituents and fluid properties found in these media (anions, dissolved metals, radionuclides, hydrocarbons, VOCs, dissolved gases, isotopes, pH, specific

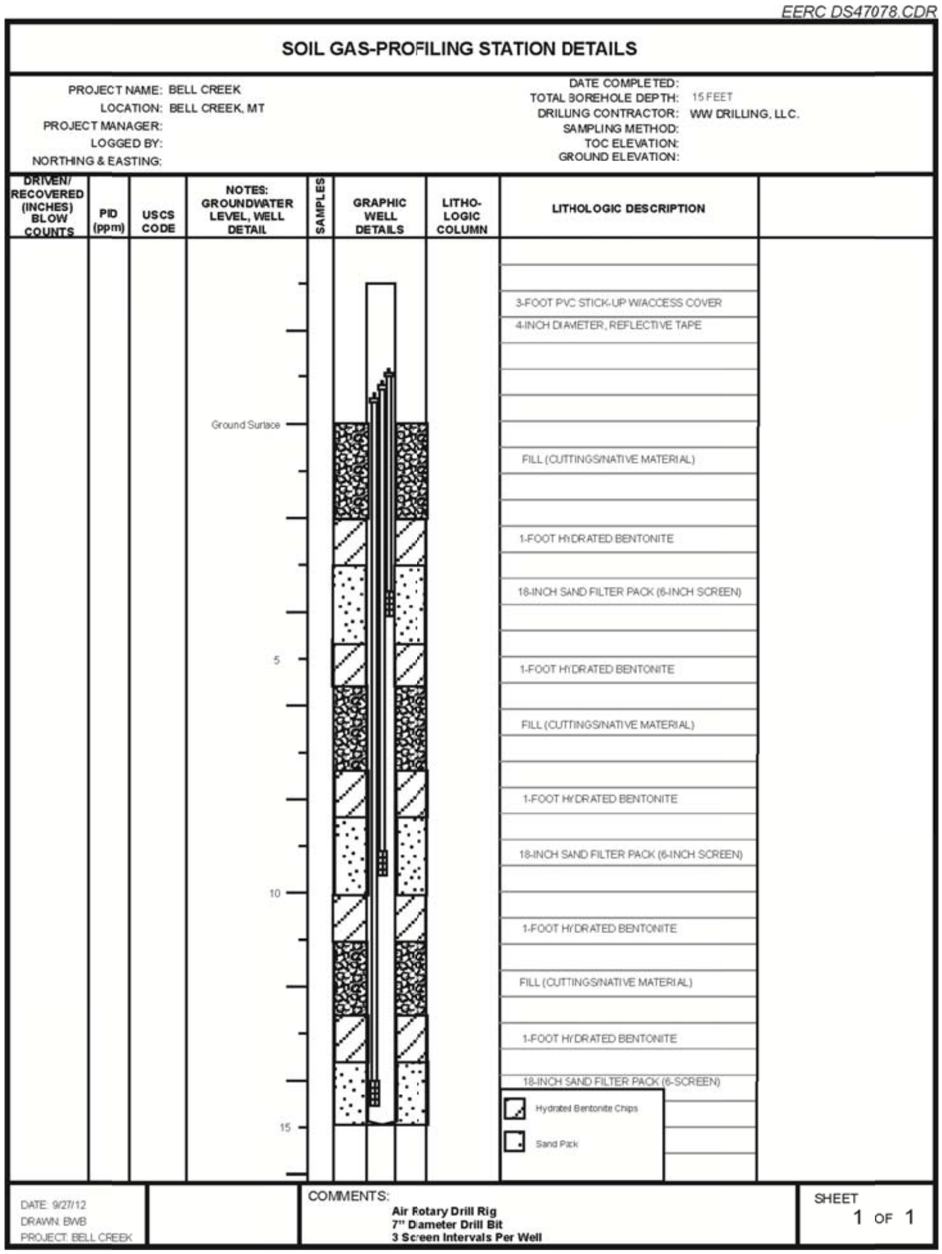

Figure 7. Schematic of the SGPS well design.

conductance [SC], conductivity, dissolved oxygen [DO], and total dissolved solids [TDS]. Standard U.S. Environmental Protection Agency (EPA) methods were used to collect these samples. Any observed changes in one or any combination of these constituents during the baseline period were interpreted as a natural biologic or nonrelated phenomenon. If changes are observed during operation, they may also be indicative of an out-of-zone fluid migration or an extension of the naturally occurring phenomenon observed during the baseline period. If such an anomaly is detected, these data can be analyzed to determine the source of the anomaly (biogenic, change in land use practices, out-of-zone migration, etc.).

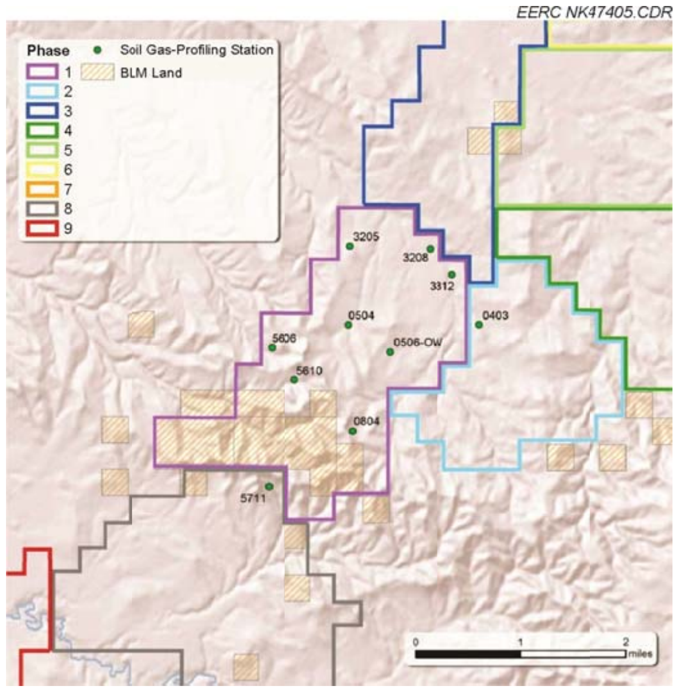

Figure 8. SGPSs located within and around the Phase 1 area, installed near existing active wells.

The collection of water samples (surface water and groundwater) consisted of filling laboratory-grade bottles with a representative sample from each sample point (standing water or well). Seasonal variations occurred; however, surface waters were impacted by this variation more than groundwater. Factors such as dramatic rises in temperature, large precipitation events, and changes in land use practices can influence surface water compositions more so than groundwater. Baseline water sampling and analyses were conducted quarterly from November 2011 to April 2013 to capture these variations, and they will be repeated annually (Table 3) during the operational phase (2013–2015).

Fieldwide Surface Water and Groundwater Monitoring

The EERC collected baseline surface water samples in the Bell Creek area at the same frequency as the soil gas sampling (Table 1). Surface water is limited in Bell Creek and consists primarily of perennial and intermittent streams, ponds (natural and impoundments for stock watering), and springs. Nine surface water sample sites were identified from a combination of aerial photography and ground-level reconnaissance (Figure 9). Sample collection procedures followed guidance outlined in EPA's standard operating procedures for surface water-sampling (Syracuse Research Corporation, 2003). Two of the surface water sampling locations were in the Phase 1 boundary.

Table 3. Water-Monitoring Overview for the Bell Creek EOR CO_2 Storage Site MVA Program[1]

Monitoring Technique	Number of Locations	Frequency (baseline)	Frequency (operational)	Measurement
Surface Water Sampling	Nine ponds and streams	Quarterly	Annually	***Field*** • YSI Professional Plus multiparameter handheld meter: temperature, pH, DO, oxidation reduction potential (ORP), SC, and TDS (calculated). • Hanna field test kit: alkalinity as $CaCO_3$, dissolved CO_2, and chloride. ***Laboratory*** • TDS, total organic carbon (TOC), total inorganic carbon (TIC), dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), total petroleum hydrocarbons (TPH), dissolved gases (methane, ethane, ethene), radionuclides (residential and Fox Hills groundwater samples only), VOCs, semi-VOCs, major cations and anions, metals and isotopes (for select surface and groundwaters, including Fox Hills): ^{2}H, ^{3}H, ^{13}C, ^{14}C, and ^{18}O.
Groundwater Sampling	– Seven stock wells – Seven residential wells	Quarterly	Annually	
Fox Hills Groundwater Well Sampling	Two	Near-monthly, starting April 2013	Near-monthly (field) and annually (lab)	

[1] Modified from *Bell Creek Enhanced Oil Recovery –Carbon Dioxide Storage Site Risk-Based Monitoring, Verification, and Accounting Review* Draft Report.

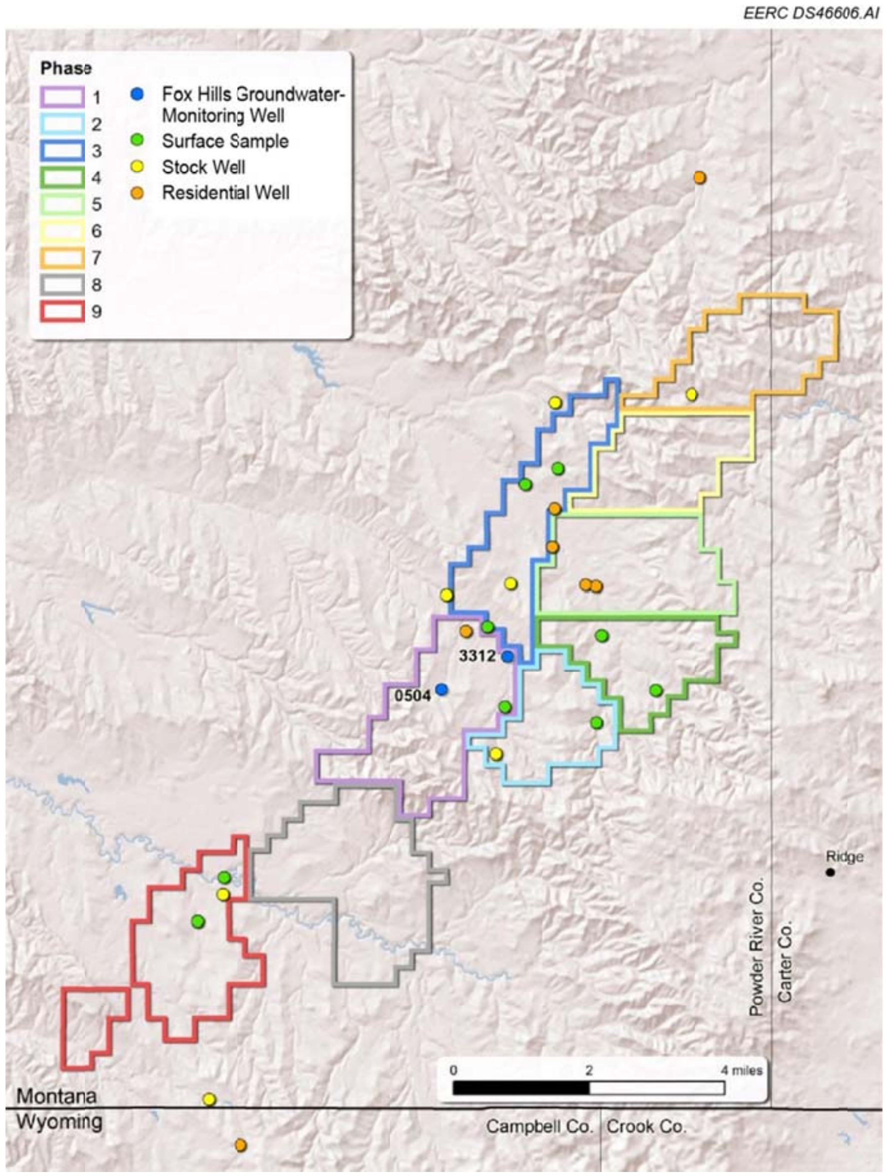

Figure 9. Groundwater-monitoring well location map.

Water quality parameters were measured both in the field and in the laboratory. Field measurements of pH, temperature, DO, SC, and calculated TDS were made using a YSI Professional Plus handheld multiparameter meter. Prior to collecting a surface or groundwater sample, the YSI meter was calibrated daily before use according to the calibration instructions provided in the user manual. Additional field measurements included dissolved CO_2, alkalinity as $CaCO_3$, and chloride, which were measured using colorimetric titration with a Hanna field test kit.

The EERC collected baseline groundwater samples in the Bell Creek area at the same frequency as the soil gas sampling (Table 1). Groundwater samples were collected from a select group of existing private water wells located in the Bell Creek oil field. A total of

14 groundwater sites were sampled during the near-surface baseline monitoring program: seven residential and seven stock wells (Figure 9). A majority of these wells were screened between 3300 to around 3500 feet above sea level in the Hell Creek Formation, with total well depths ranging from 126 to 700 feet below ground surface. Only one residential well was located in the Phase 1 area. Because of differing completion of individual wells, downhole groundwater-sampling methods could not be used. Samples were collected directly from a spigot or valve using the well's submersible pump or another existing mechanical method. In residential wells, drinking water samples were collected upstream of any household treatment system (water softener, etc.).

Fox Hills Groundwater Monitoring

Two deep Fox Hills groundwater-monitoring wells were installed during the first quarter (Q1) of 2013 in the Phase 1 area of the Bell Creek Field to further enhance monitoring capabilities. These groundwater wells have been completed in the Fox Hills Formation, the deepest USDW, and was first sampled during April 2013. The Fox Hills Formation and the overlying Hell Creek Formation (Figure 4) are the principal water-yielding Upper Cretaceous aquifers in the region of the Bell Creek oil field.

The monitoring wells are colocated on pads associated with Oil-Producing Wells 05-04 and 33-12 (Figure 9). These pads are sited close to ravines that will allow for surface discharge of casing purge volumes and potential low flows of groundwater that would be required for potential continuous monitoring throughout the CO_2 injection period. Monitoring Well 05-04 was drilled to a total depth of 820 feet below ground surface, into the Pierre Shale just below the Fox Hills Formation (Figure 10). The 80-foot screened interval is from 680 to 760 feet, the middle of the Fox Hills aquifer. Monitoring Well 33-12 was drilled to a total depth of 600 feet, the bottom of the Fox Hills aquifer at that location. The top of the Fox Hills at that location is 480 feet below ground surface, and the well was screened from 540 to 600 feet.

The wells were fitted with submersible pumps and will be sampled monthly for field analyses and annually for laboratory analyses. Groundwater data in the Phase 1 development area and data for deep sources of drinking water are underrepresented within the groundwater-monitoring program because of limited well availability. Information gathered from these wells will be used to provide baseline characteristics for deep sources of drinking water in the area and will further strengthen the groundwater-sampling program. Baseline and operational water chemistry analysis (both field and laboratory) will provide key data for detecting a potential vertical CO_2 migration event.

During Q1 of 2013, the EERC developed a laboratory test plan to determine the utility of using changes in groundwater pH and SC as a tool to detect and quantify a potential vertical migration of CO_2. As part of the near-surface-monitoring program, continuous data logging of pH and SC for the two Fox Hills groundwater-monitoring wells in Phase 1 will be assessed; pH and SC measurements offer an easy and relatively robust way to monitor potential changes in groundwater chemistry that could be indicative of a potential vertical CO_2 migration.

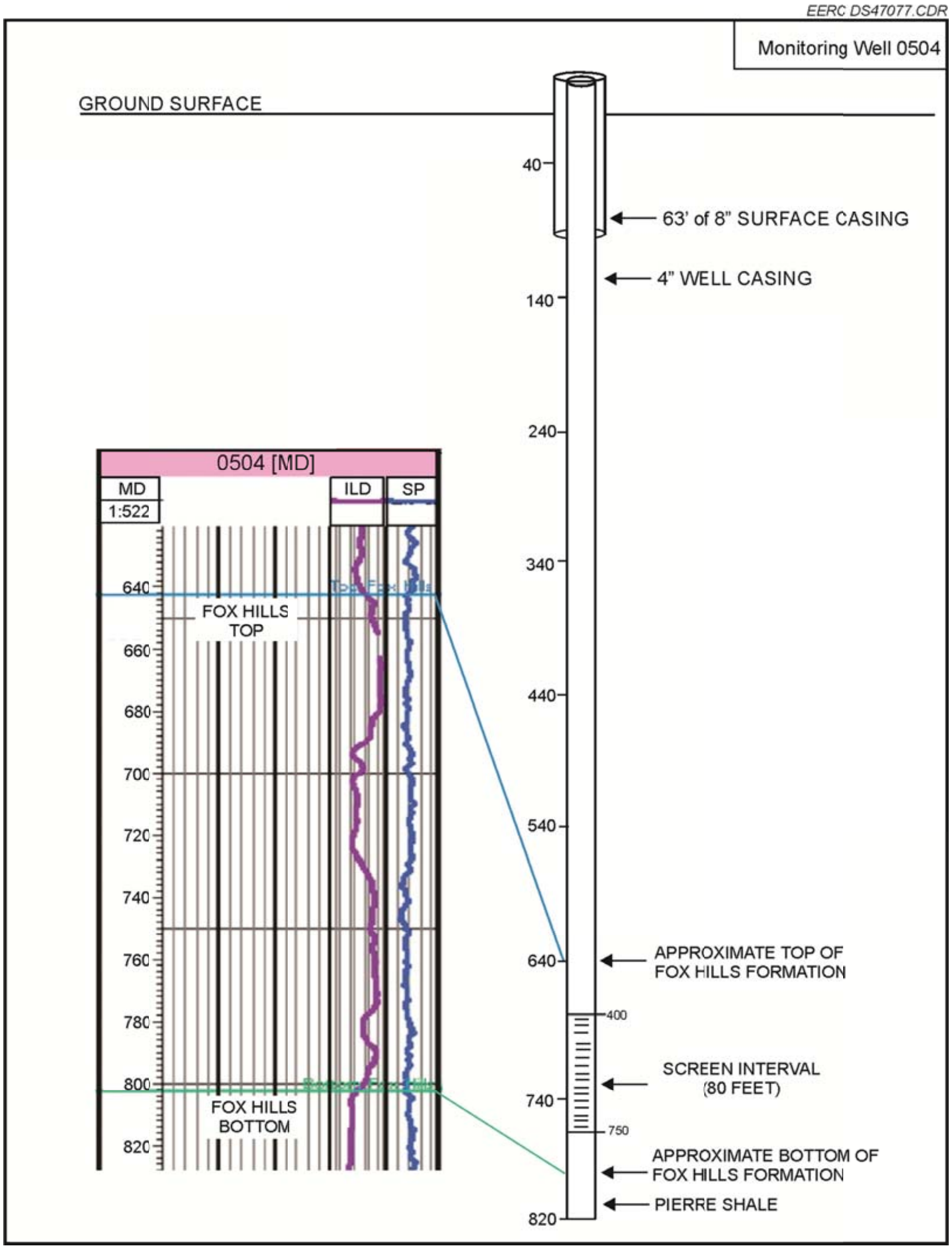

Figure 10. Completion detail for Fox Hills Monitoring Well 05-04.

Deep Subsurface-Monitoring Techniques

The EERC has developed a deep subsurface MVA program to address technical subsurface risk and monitor CO_2 and fluid migration both in the reservoir and in the subsurface as a whole. The goal of the deep subsurface MVA program is to effectively monitor and track the movement of injected CO_2 and reservoir fluids in the deep subsurface in order to evaluate the recovery efficiency of the CO_2 EOR program, demonstrate safe and effective storage, identify fluid migration pathways, and determine the fate of injected CO_2. Both baseline and time-lapse data acquisitions are necessary to optimize the utility of the MVA program. The majority of baseline data acquisitions focus on minimizing the variance between preinjection and injection conditions resulting from pressure and fluid changes in the reservoir.

The deep subsurface MVA program (Table 4) utilizes a combination of wellbore technologies, such as pulsed neutron tools, downhole pressure and temperature monitoring, and 3-D vertical seismic profile (VSP) acquisition, to measure reservoir changes during injection, track the vertical and lateral extent of fluid and CO_2 movements during the injection process, and account for injected CO_2. The data acquired from these wellbore technologies are then evaluated and integrated into the various geomodeling activities (reservoir modeling, 3-D MEM [mechanical earth model], and the full-field geologic model). Some data can be directly inputted into the geomodeling software, while other data types, such as historic reservoir pressure data, are matched within models through reservoir simulation during the history-matching process. All of these inputs serve to constrain modeling and simulation predictions and guide future MVA activities.

Data acquired also help to bind simulation predictions in the context of real-world data. Key parameters are used to update modeling and simulation work on an iterative basis in order to identify and eliminate variances between the real-world physics of injection and predicted behavior of the CO_2, reservoir fluids, and rock matrix. This iterative process allows for decreased uncertainty in predictions.

Additionally, monitoring data provide insight into mechanisms that could contribute to premature CO_2 aerial sweep during EOR activities, ultimate CO_2 storage capacity, an accurate assessment of long-term retention, and the ability to predict CO_2 movement and chemical interactions within the reservoir after site closure.

Pulsed-Neutron Logs (PNLs)

The EERC has collected baseline PNLs from total well depth to the surface casing shoe from 27 wells in the Phase 1 area; an additional 3–13 wells are anticipated to be logged prior to the start of injection, totaling up to 30–40 wells including the monitoring well 05-06 OW (Figure 11). Two time-lapse repeat surveys are anticipated, one of which will occur shortly after breakthrough of CO_2 to the production well. The other will be determined based on predictive simulation results to determine the swept volume of the reservoir and/or to determine timing of time-lapse seismic surveys.

Table 4. Deep Subsurface-Monitoring Overview for the Bell Creek EOR CO_2 Storage Site MVA Program[1]

Monitoring Technique	Number of Locations	Frequency (baseline)	Frequency (operational)	Measurement
PNL	30–40 wells (including 05-06 OW)	Once	TBD[2]	Water, oil, and CO_2 saturations near wellbore.
Wellhead Pressure, Temperature, and Flow	All active injection and production wells, fieldwide	Near-continuous	Near-continuous	Wellhead pressure, temperature, and flow (surface casing pressure, production casing pressure, flow-line pressure, tubing pressure, mass flow, recycling volumes, and production volumes).
Downhole Pressure and Temperature, Specific Depth	05-06 OW well at – Belle Fourche: 4110 ft – Muddy 10: 4515 ft – Muddy 30: 4535 ft	5-minute intervals	5-minute intervals	Downhole pressure and temperature.
Downhole Temperature, Profile	05-06 OW well at 1-meter vertical resolution from 4750 ft to the surface	4-hour intervals	4-hour intervals	Temperature profile along the wellbore via fiber optic system.
BHP Survey	Fieldwide	TBD	TBD	Bottomhole pressure.
3-D Surface Seismic	40 square miles	Once	TBD	3-D surface seismic survey.
3-D VSP	Two wells: – 05-06 OW – 04-03 OW	Once	TBD	Downhole seismic acquisition at the listed wells.
Geomodels and Simulation	Fieldwide to surface	Continually evolving	As data come in and are incorporated (at least yearly)	Integration of all measurements and allow for the comparison of methods.

[1] Modified from *Bell Creek Enhanced Oil Recovery –Carbon Dioxide Storage Site Risk-Based Monitoring, Verification, and Accounting Review* Draft Report.
[2] To be determined (timing and quantity of repeat measurements are still under consideration).

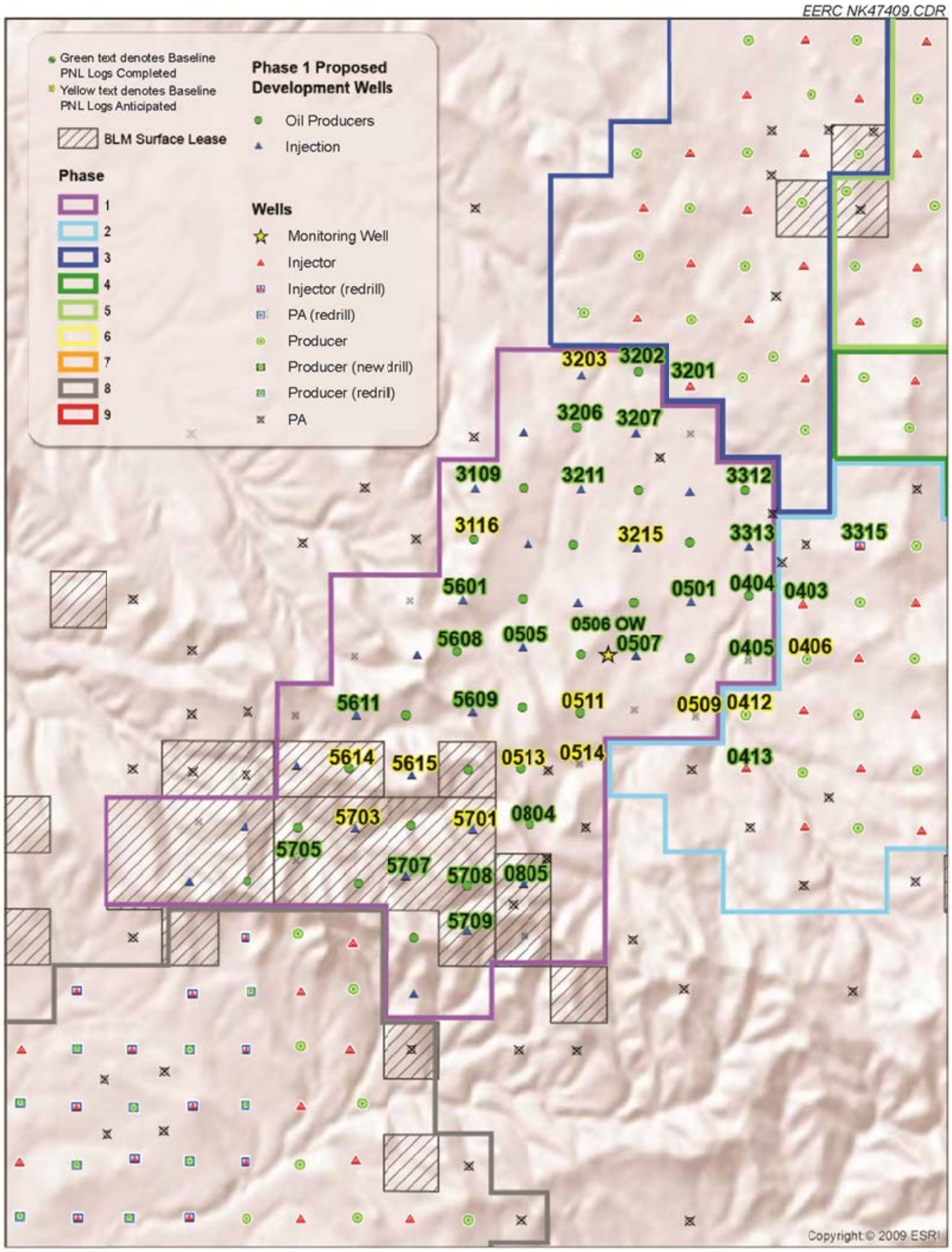

Figure 11. Map illustrating the completed and anticipated time-lapse pulsed-neutron data acquisitions.

PNLs are acquired via wireline conveyance in conjunction with a crane truck. Tool specifications allow for acquisition through 2⅞-inch tubing and are run with wellhead pressure control equipment (wireline blowout preventer [BOP], lubricator, and grease injection). Logging operations require each well be sequentially taken off-line (production or injection) and take approximately 8 hours per well from rig up to rig down. Scheduling and acquisition is coordinated between Denbury, the EERC, and the logging service provider to allow for minimal impact to commercial CO_2 EOR operation.

PNLs provide a quantitative assessment of water, oil, and CO_2 saturations in the near-wellbore environment. Applications include the following:

- Monitoring changes in water, oil, and CO_2 contacts over time.

- Ability to identify unswept oil along a vertical cross section of reservoir:
  - Determine CO_2 storage efficiencies.
  - Determine EOR effectiveness.
  - Identify channeling between lithofacies and/or causes of early CO_2 breakthrough.
  - Aid in determination of swept reservoir volume and effective storage volume.

- Ability to identify vertical CO_2 migration along the wellbore into overlying formations and/or locate accumulations of CO_2 into overlying formations, which have migrated vertically above the top of the cement (if present).

- Provide an indication of cement integrity and/or identify wells that are candidates for remediation activities (if present).

- Provide a means to correlate seismic data with quantitative CO_2 saturation and the vertical distribution of CO_2 within the reservoir.

- Provide a near-wellbore saturation history for predictive simulation history match.

- Provide a means to identify horizontal fluid migration with Phase 1, or into Phases 2, or 3, or 8.

- Identify production wells in areas where the reservoir is not being effectively swept through EOR flood.

- Provide an indication of flow boundaries in the interwell environment.

- Identify lithofacies in production wells that are not accepting injection.

- Identify vertical flow boundaries in the near-wellbore environment.

Wellhead Pressure, Temperature, Flow Rates, and Well Testing

Real-time wellhead pressure, temperature, flow, and well test data (surface casing pressure, production casing pressure, flow-line pressure, tubing pressure, mass flow, recycling volumes, and production volumes) will be collected periodically for all active injection and production wells fieldwide. These measurements were accessed with permission from Denbury and will be collected during the operational phase of the project at the same frequency. Applications include the following:

- Ability to identify injectivity or well integrity issues.
- Ability to correlate injection pressure with downhole and reservoir pressures.
- A valuable high-density input for injection and production pressures and volumes for predictive simulation history matching.
- Ability to predict the physical properties and phase behavior of injected CO_2.
- Ability to quantify injected and produced volumes of CO_2, oil, and water.
- Provide an indication of CO_2 arrival at production wells.
- Ability to monitor for pressure communication within and between development phases.

Downhole Pressure and Temperature Gauges and Fiber Optic Distributed Temperature

Three permanent downhole pressure and temperature gauges as well as a distributed fiber optic measurement system are deployed in the 05-06 OW well for permanent downhole monitoring (PDM). Production and injection wells 05-06 and 05-07, offset to the 05-06 OW well, are also being considered for PDM; however, deployment is contingent on operation constraints and well completions, which are currently being evaluated in conjunction with Denbury.

The downhole 05-06 OW pressure and temperature gauges provide real-time pressure and temperature data at a 5-minute measurement frequency for three intervals: 4110 feet in the Belle Fourche Formation, which corresponds to a zone of permeability overlying the Muddy Formation; 4515 feet in the BC10 interval of the Muddy Formation; and 4535 feet, which corresponds to the BC30 interval of the Muddy Formation. The distributed-temperature fiber optic measurement system provides a temperature profile along the wellbore. Currently, the system is acquiring measurements at a 1-meter resolution from a depth of 4750 feet to the surface at a frequency of every 4 hours.

Applications for PDM include the following:

- In situ pressure and temperature data:
  - A means to correlate wellhead injection and production pressures to reservoir pressure.
  - A valuable input of interwell reservoir pressure for predictive simulation history matching.
- Potential to provide an indication of CO_2 arrival at the 05-06 OW well.
- Potential to provide an indication of CO_2 channeling and unswept oil along a vertical cross section within the reservoir.
- Provide an indication of out-of-zone fluid migration along the 05-06 OW wellbore or CO_2 losses into the next overlying zone of permeability underlying the primary seal.
- Provide an input for geomechanical assessments.
- Ability to measure the pressure/temperature regime of the reservoir.
- Assess zonal pressure isolation between various lithofacies of the Muddy Formation.

Bottomhole Pressure Surveys

Periodic bottomhole pressure (BHP) surveys, collected as part of the commercial EOR process, will be monitored throughout the field to provide a means to monitor reservoir pressure at selected wells. A BHP survey consists of obtaining pressure and gradient information downhole. Timing, quantity, and location of BHP surveys are determined by Denbury as part of the commercial EOR project.

Applications include the following:

- Provide an indication of connectivity between various development phases of the Bell Creek Field.
- Establish an average reservoir pressure for a producing area.
- Provide a valuable input of downhole reservoir pressure for predictive simulation history matching.
- Provide a means of monitoring pressure response of the reservoir during water injection.

3-D VSP

Baseline and repeat 3-D VSPs will be conducted with a downhole geophone array deployed into the 05-06 OW and 04-03 OW wells (Figure 12). A baseline survey was collected in each of these wells during May 2013, with at least one time-lapse repeat being conducted in 2013 and 2014. The VSP equipment will consist of a 50-level retrievable geophone array in the 05-06 OW well and a permanently installed 50-level geophone array cemented into the 04-03 OW well. The VSP data will allow for calibration and enhanced processing of the time-lapse 3-D surface seismic data, seismic characterization of subsurface structure, and for time-lapse seismic images of CO_2 saturation changes. The permanently installed geophone array may also be used for passive seismic monitoring of the field. Timing and quantity of repeat surveys are still under consideration and will be guided by reservoir response to CO_2 injection and coincide with time-lapse surface seismic and PNL activities.

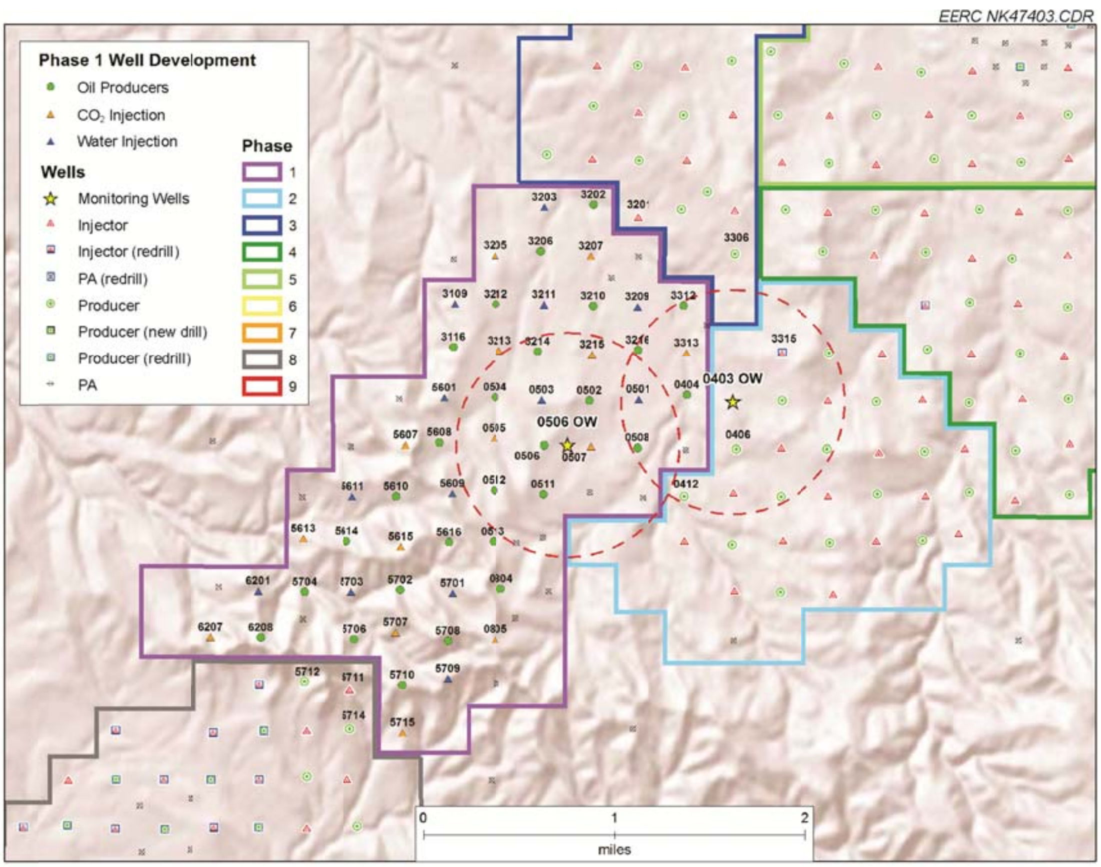

Figure 12. Preliminary survey design of the 3-D VSP seismic surveys. Red circles illustrate maximum illumination at reservoir depth.

Time-lapse 3-D VSP surveys utilizing both retrievable and permanently deployed geophone arrays will allow the monitoring of CO_2 migration pathways between select production and injection wells. Applications include the following:

- Identify horizontal channeling of CO_2 between an injection and production well pair.
- Identify unswept zones between an injection and production well pair (effective storage capacity).
- Monitor the shape of the areal CO_2 flood front and streamlines.
- Ability to extrapolate pulsed neutron data into an interwellbore environment.
- Provide a means of correlating surface seismic data to higher-resolution VSP data and higher-resolution VSP data to vertical CO_2 distribution via PNLs.
- Provide an input for interwell reservoir saturation for predictive simulation history matching.
- Identify the distribution of heterogeneities and lateral flow boundaries between an injection and production well pair.

3-D Surface Seismic Survey

A 40-square-mile 3-D seismic survey was collected over a portion of the Bell Creek field centered on the Phase 1 area (Figure 13) in August 2012. Timing, quantity, and location of repeat surveys are still under consideration. The next repeat survey is tentatively planned for the first quarter of 2014 and will be carried out by Denbury. Repeat surveys will consist of smaller areas of interest within the larger baseline seismic extent.

Time-lapse 3-D surface seismic survey data provide a qualitative estimate of areal CO_2 saturation changes in the interwellbore environment as well as updip and downdip of the field. Applications include the following:

- Identify horizontal channeling of CO_2 between multiple injection and production wells.
- Identify unswept zones between injection and production well pairs.
- Monitor the shape of the areal CO_2 flood front, streamlines, and lateral migration pathways.
- Monitor the shape of the CO_2 flood front.
- Extrapolate pulsed neutron data into interwellbore environment.

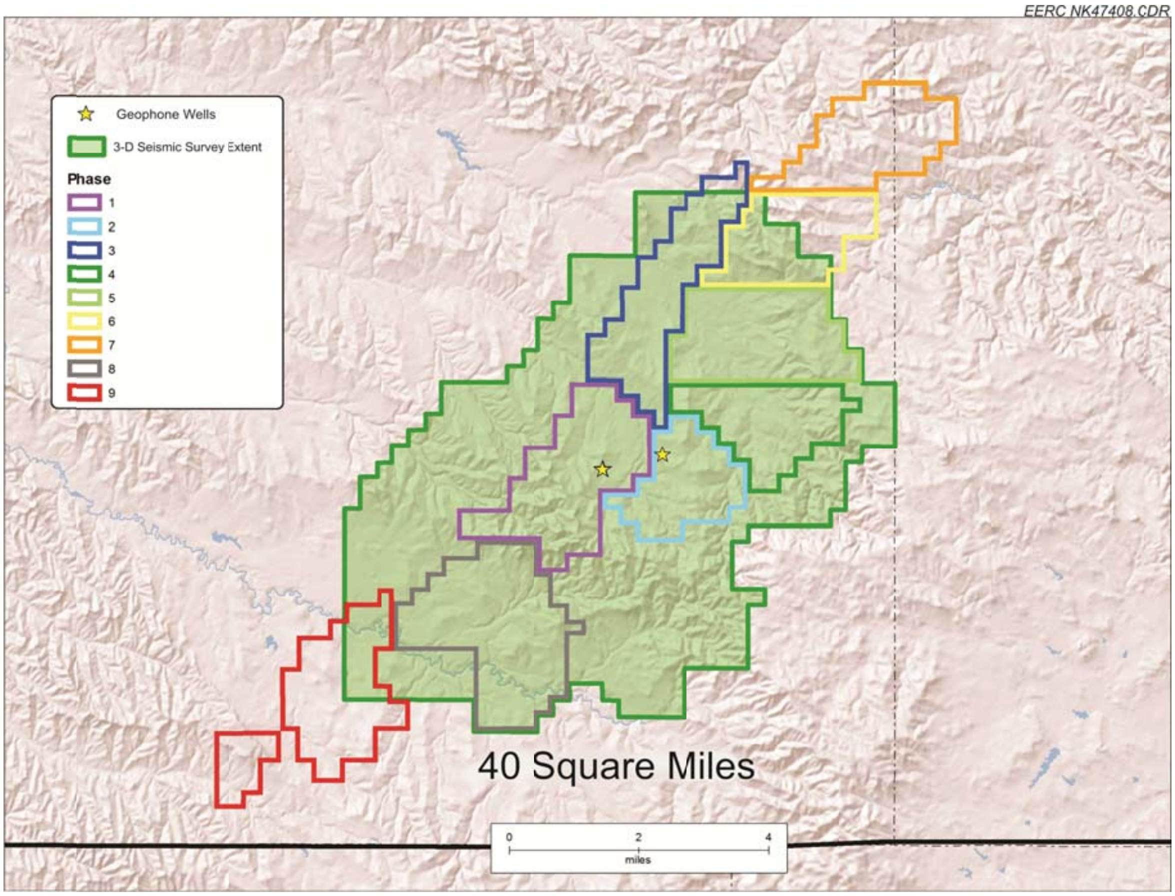

Figure 13. Baseline 3-D surface seismic survey outline.

- Provide a means of correlating surface seismic data to higher-resolution VSP surveys and to vertical CO_2 distribution via PNLs.
- Provide an input of interwell reservoir saturation changes for predictive simulation history matching.
- Identify the distribution of lateral heterogeneities and flow boundaries in the interwellbore environment.
- Identify production wells in portions of the reservoir that are not experiencing effective EOR flood.
- Improve accuracy of geologic model as a direct structural geology input.
- Corroborate other model inputs from other geological characterization activities as well as improve data integration between varying data sources.

- Provide a verification method for reservoir simulation activities, including history matching and CO_2 flood simulations.

Additional Monitoring Activities at the Bell Creek Field

Additional monitoring activities in the Bell Creek Field currently under evaluation include the following:

- A tracer flood study injecting gas-phase chemical tracers into 21 injection wells in the Phase 1 area and monitoring CO_2 arrival times and concentrations in all production wells in Phase 1. The operational monitoring frequency will be on a periodic basis. The tracer flood program will not look at vertical migration into overlying reservoirs but rather provide information on effective storage efficiency and capacity by evaluating flow paths within the reservoir.

- Installation of between 0 and 4 passive seismic stations to monitor for induced seismicity on a near-continuous basis. Seismicity is not expected to be induced because of the reservoir history and the geomechanical properties of the formation and surrounding strata. The permanently installed 50-level geophone array in the 04-03 OW well may also be used for passive seismic monitoring of the field.

Ongoing activities that are guiding MVA techniques employed throughout the Bell Creek Field include the following:

- Geologic modeling and predictive simulation (plume extent, injection volumes, breakthrough times, etc.) have been utilized to aid in the development of monitoring long-term injected CO_2 storage and EOR. A robust and iterative site characterization program was undertaken beginning in 2010 to provide critical data for the 3-D static geological model (Version 1) which is focused in the Phase 1 area (Hamling and others, 2012). Based on insights gained from the Version 1 model, a second iteration 3-D geological model (Version 2) representing the entire field is being constructed. The log and core data acquired from the newly drilled monitoring well and lidar (light detection and ranging) survey are expected to greatly improve this new model (Saini and others, 2012).

- A geomechanical assessment of the field is currently under way. A 3-D mechanical earth model (MEM), which incorporates the entire Bell Creek Field, is currently being constructed and will be completed when additional well logs and seismic data become available. Following the completion of the 3-D MEM, a comprehensive geomechanical analysis will be performed to match, monitor, and predict the geomechanical response from the reservoir, overlying formations, and at the surface. Additionally, predictive geomechanical simulations will be designed and performed that will help guide and update the MVA plan, evaluate potential risk scenarios, and ensure injected CO_2 remains stored within the reservoir (Ge and others, 2013).

- Vintage well log, core analysis, and well file data for over 700 wells within and around the field were evaluated in conjunction with characterization and predictive simulation activities to identify key technical subsurface risks:

  1. Capacity: a loss of storage volume with respect to initial estimates.

  2. Injectivity: the cumulative loss of CO_2 injectivity for some or all of the injection wells.

  3. Retention: the retention of CO_2 injected into the reservoir.

  4. Containment: outside of the planned storage container.

  5. Seismic: induced seismicity resulting from CO_2 injection.

  6. Public perception.

CONCLUSION

The PCOR Partnership philosophy of MVA dictates that any and all insight gained from an effective MVA program is integrated into modeling and simulation activities, which, in turn, provides higher confidence in prediction results and allows for increased understanding of technical project retention metrics. Baseline and operational MVA activities at the Bell Creek oil field are targeting observation of CO_2 migration from varying perspectives utilizing a wide variety of techniques. This approach is being carried out to observe the nature of CO_2 movement within the reservoir, gain the greatest possible understanding of key technical subsurface-monitoring techniques, and evaluate the relationships that exist between EOR and CCS operations. The Bell Creek MVA program is also designed to integrate into commercial operations to minimize the impact to the EOR operator. Furthermore, the data acquired will be used to both validate and improve the effectiveness of characterization, modeling, monitoring, and risk assessment techniques.

Any robust monitoring program requires the use of multiple synergistic technologies to identify, confirm, locate, and quantify the behavior and interactions of fluids and rock matrices in the subsurface. The combined surface, near-surface, and deep subsurface MVA program outlined in this activity is designed to address technical subsurface risks specific to the Bell Creek combined CO_2 EOR operation and the incidental CO_2 storage project. The technologies selected have been matched with specific monitoring objectives and designed to operate in a complementary manner. In addition, the wide array of MVA techniques employed at Bell Creek put the PCOR Partnership in the best possible technical position to detect potential out-of-zone migration in its early stages and deploy mitigation strategies if necessary.

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