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Overview of the Bell Creek combined CO_2 storage and CO_2 enhanced oil recovery project

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Abstract

The Plains CO_2 Reduction (PCOR) Partnership, led by the Energy & Environmental Research Center, is working with Denbury Onshore LLC (Denbury) to characterize and monitor a large-scale CO_2 enhanced oil recovery (EOR) and CO_2 storage project at the Bell Creek oil field located in southeastern Montana, USA. Denbury owns and operates the field and will carry out the commercial EOR project. The PCOR Partnership is applying an integrated approach to site characterization, modeling, predictive simulation, risk assessment, and monitoring to improve understanding of the interrelationship between CO_2 storage and EOR in a clastic reservoir.

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1. 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 CO_2 storage at the Bell Creek oil field (Figure 1). Denbury owns and operates the field and will carry out the commercial EOR project. In addition, a technical team that includes Denbury, the EERC, and others is conducting a variety of activities to determine baseline reservoir characteristics, including predictive simulations and monitoring of the CO_2 storage component of the project in parallel with Denbury activities focused on the EOR project. These activities will facilitate assessment of various potential injection schemes, guide monitoring strategies, and determine the ultimate fate of injected CO_2. Denbury will carry out the injection and production operations in a phased approach (nine planned development phases) (Figure 2), while the EERC will provide support for

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the integrated site characterization, modeling, predictive simulation, and risk assessment and will aid in the development of the monitoring, verification, and accounting (MVA) plan to address the key technical subsurface risks of CO2 storage associated with EOR.

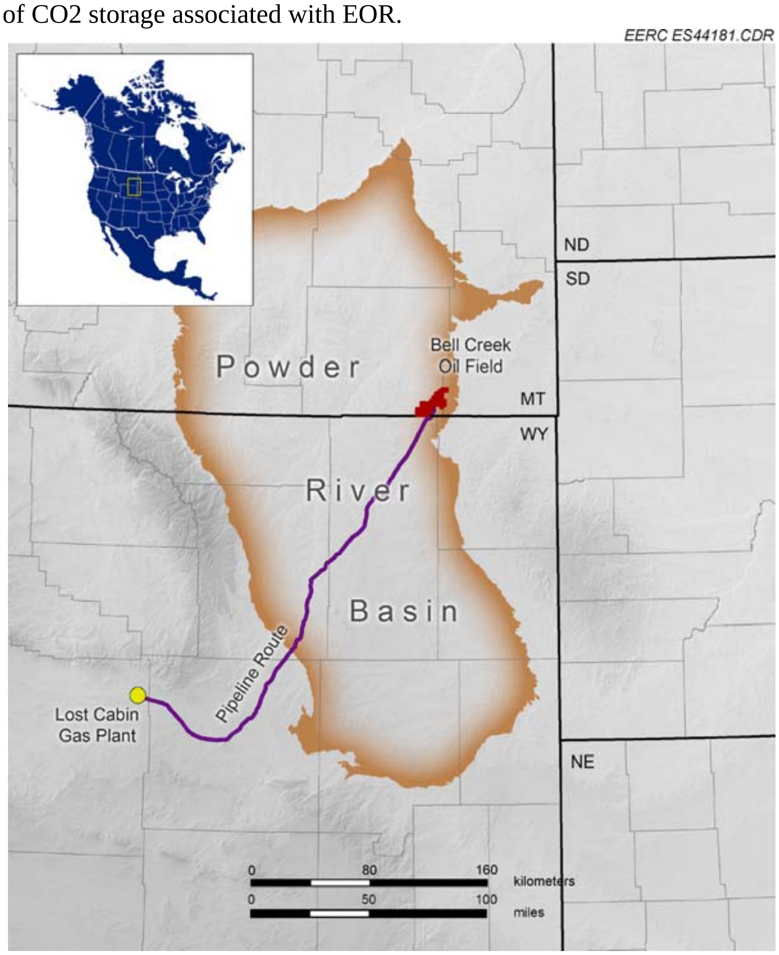

Fig. 1. Map illustrating the location of the Bell Creek oil field in relation to the ConocoPhillips-owned Lost Cabin gas-processing plant and the Greencore pipeline route. The Bell Creek oil field is located in the Powder River Basin in southeastern Montana and transverses portions of both Powder River and Carter Counties [1]

The Bell Creek oil field in southeastern Montana is a subnormally pressured reservoir with significant hydrocarbon accumulation (353 million barrels STOOIP [stock tank and original oil in place]) that lies near the northeastern corner of the Powder River Basin (Figure 1) [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 (solution gas drive) and secondary (continuous waterflood and two polymer flood pilot tests) recovery have resulted in reservoir decline (56,000 barrels oil/day in 1968 to 975 barrels oil/day in 2012) and has now led to the planned implementation of a CO_2 injection-based tertiary oil recovery project for simultaneous EOR and CO_2 storage purposes. To date, the cumulative oil production total for the field is 133.4 million barrels (37.8%).

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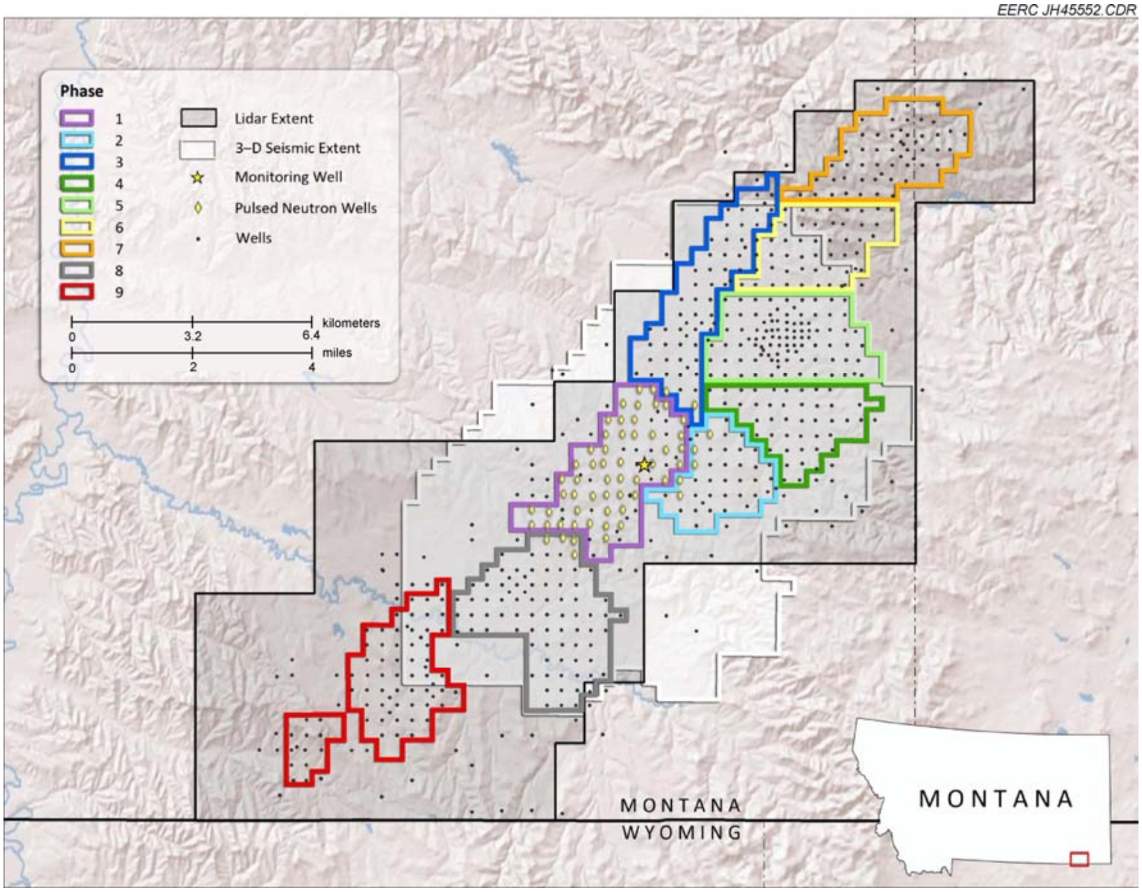

Fig. 2. Map illustrating the phased CO_2 development program of the Bell Creek oil field. The extent of the LIDAR (Light Detection and Ranging) survey and baseline 3-D seismic survey are also shown along with candidate wells for the pulsed neutron well log campaign. The location of the 0506 OW monitoring and characterization well drilled in 2011 is denoted by a yellow star and candidate wells for pulsed neutron well logging are highlighted in yellow (modified from [1])

1,416,000 m^3 (50 million cubic feet) of CO_2 a day will be delivered to the site via pipeline from the Lost Cabin gas plant in Fremont County, Wyoming (Figure 1), where it is separated from the process stream during refinement of natural gas [1]. CO_2 will be injected into a oil-bearing sandstone reservoir in the Lower Cretaceous Muddy (Newcastle) Formation at a depth of approximately 1310–1372 meters (4300–4500 feet). It is expected that the reservoir will be suitable for miscible flooding conditions with an incremental oil production target ranging from 30 to 50 million barrels. The activities at the Bell Creek oil field will inject an estimated 1 million tonnes (1.1 million tons) of CO_2 annually, much of which will be permanently stored at the end of the EOR project.

Within the boundaries of the Bell Creek oil field, the Muddy Formation is dominated by high-porosity (25%–35%) high-permeability (100–1175 mD) sandstones deposited in a near-shore marine environment [2]. 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 32 km (20 miles) [2]. Stratigraphically, the Muddy Formation in the Bell Creek oil field 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 initial reservoir pressure in the Muddy Formation was 8.27 MPa (1200 psi), which is significantly lower than the regional hydrostatic pressure regime (14.5 MPa at 1372 m [2100 psi at 4500 ft]) [3]. A detailed study conducted as part of the Bell Creek project concluded the Bell Creek oil field is a hydrodynamically isolated system and has effective reservoir seals that have successfully retained vast hydrocarbon accumulations over geologic time. This evidence suggests that in the absence of fracturing, the reservoir will provide an effective and safe enclosure for injected CO_2 and does not appear to pose risk to reservoir and seal integrity during CO_2 injection.

The overlying Upper Cretaceous Mowry Formation shale provides 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 3) [4].

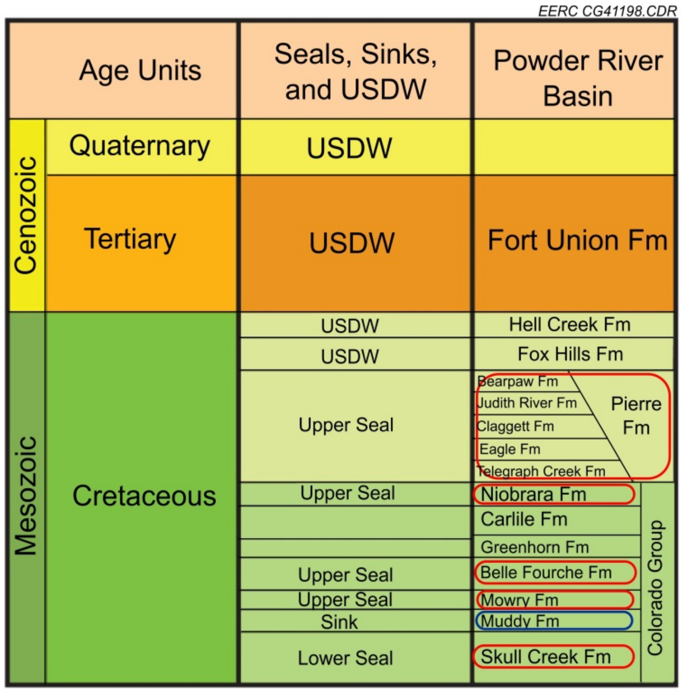

Fig. 3. Stratigraphic column of the Powder River Basin, Montana. Sealing formations are circled in red, and the primary sink formations are circled in blue. Formations bearing underground sources of drinking water (USDW) are also identified [1]

2. Integrated approach

The PCOR Partnership has developed an approach that integrates site characterization, modeling and predictive simulation, risk assessment, and MVA into an iterative process to produce meaningful results for large-scale CO_2 storage projects (Figure 4) [1]. Elements of any of these activities play a crucial role in the understanding and development of the others. The modeling and simulation activities were developed to 1) identify areas where more site characterization data are needed, 2) aid in the identification of potential subsurface risks such as out-of-zone fluid migration, and 3) help in the development of effective monitoring strategies.

The reservoir-monitoring program (partially guided by modeling, predictive simulation, and risk) will utilize preinjection baseline data set(s) and a staged-injection monitoring approach to allow for time-lapse data acquisitions collected during key intervals of the EOR operation. The surface-, near-surface-, and reservoir-monitoring programs are engineered to establish the relationship between a CO_2 EOR process and long-term storage of CO_2, have minimal impact on the commercial EOR project, provide value to both the EOR and CO_2 storage project, while addressing key technical risks, limited wellbore access, and reservoir complexities experienced during an active large-scale EOR project.

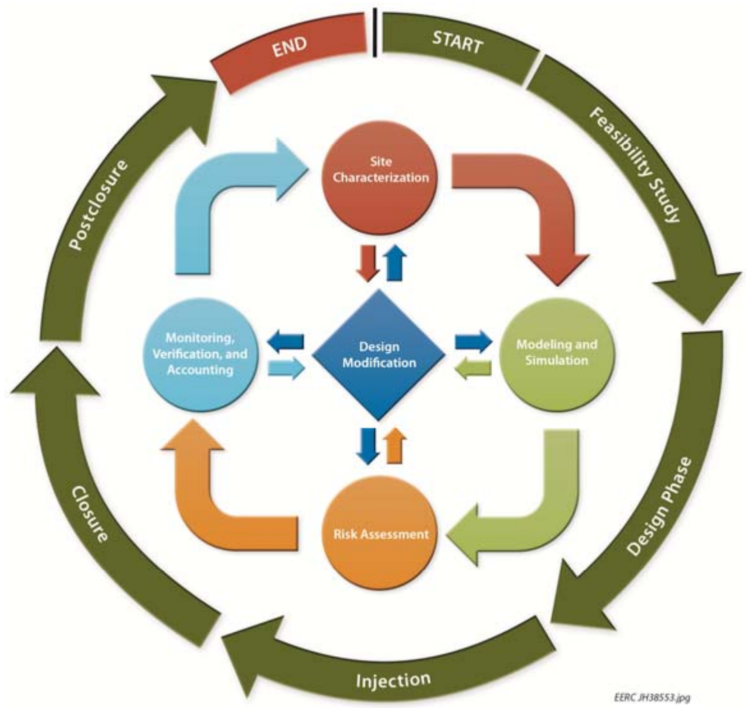

Fig. 4. Project elements of the Bell Creek project. Each of these elements feeds into another, iteratively improving results and efficiency of evaluation by reducing uncertainty throughout the project life cycle [1]

The Bell Creek combined CO_2 EOR and CO_2 storage project provides a unique opportunity to develop a set of cost-effective monitoring techniques for large-scale (>1 million tonnes a year) storage of CO_2 in a mature oil field in conjunction with EOR. The results of the Bell Creek project will provide insight regarding the impact of large-scale CO_2 injection on sink integrity, monitoring techniques, and regional applicability of implementing successful CO_2 storage projects within the context of EOR. The integrated process will be iterated and refined through each incremental stage of the project, from initial planning to injection and through postclosure.

3. Site characterization

The sedimentary succession in the Bell Creek area consists primarily of sandstones and shales. A stratigraphic column of the portion of the Powder River Basin to which the Bell Creek oil field is in close proximity is provided in Figure 3. A robust and iterative site characterization program was undertaken beginning in 2010 to provide critical data for the geological model representative to the Bell Creek oil field and relevant to CO_2 storage through an EOR process. Key activities include the following:

- Vintage well log, core analysis, and well file data for over 700 wells within and surrounding the Bell Creek oil field were incorporated into the geological model.
- A 194-square-km (75-square-mile) LIDAR survey was collected over the field in July of 2011 and was utilized to correct well location and elevation data throughout the field, significantly improving

structural interpretations of the reservoir. The survey also aided in identifying the locations of plugged and abandoned wellbores that could be subsequently targeted by the monitoring program.

- A monitoring and characterization well was drilled in the Phase 1 development area in December of 2011
(Figure 2). A full suite of modern well logs, 33.5 m (110 feet) of 10.16-cm (4-inch)-diameter core and 47 sidewall cores were acquired through the Mowry, Muddy, and Skull Creek Formations. Modern, high-resolution data sets for sink and seal formations within the field allowed for the calibration of vintage well log and core analysis data throughout the field. Three casings conveying pressure/temperature gauges and a fiber optic distributed temperature system were also deployed during completion to provide critical reservoir characterization data prior to and during injection.
- A 103.6-square-km (40-square-mile) 3-D seismic survey was collected in August of 2012 to further aid in structural interpretation and to provide a baseline data set for future time-lapse CO_2 monitoring. In anticipation of the survey, a seismic source test and check shot survey was performed in December of 2011 to evaluate data quality utilizing vibroseis, minivibroseis, and dynamite sources.
- Acquisitions of 62 pulsed neutron well logs are planned for the fall of 2012. The pulsed neutron well logs will provide modern gamma ray and porosity data for most wells in and around the Phase 1 development area. Pulsed neutron well logs will provide a valuable baseline data set for monitoring CO_2, water, and oil saturation changes during injection.
- Acquisition of two 3-D vertical seismic profile (VSP) seismic surveys along with the installation of a permanently installed geophone array is planned for the fall of 2012. The baseline 3-D VSP seismic surveys will allow for time-lapse data acquisitions for CO_2 monitoring as well as passive seismic monitoring during injection.

4. Modeling and predictive simulation

With the goal of providing a comprehensive assessment of CO_2 storage behavior and potential in conjunction with Denbury's EOR efforts, modeling and numerical simulation are being utilized to 1) characterize and model the study area using advanced geological modeling; 2) develop a robust pressure, volume, and temperature (PVT) model to predict miscibility behavior of the CO_2–Bell Creek crude system and to aid in compositional simulation; and 3) history matching the constructed dynamic reservoir model. Predictive simulations in turn will be utilized to aid in the development of effective strategies for monitoring long-term behavior of injected CO_2 during the implementation of an integrated CO_2 EOR and long-term CO_2 storage project in the subnormally pressured Muddy Formation at the Bell Creek oil field.

In order to more accurately evaluate the efficiency of large-scale CO_2 injection for simultaneous CO_2 EOR and CO_2 storage in the Muddy Formation at the Bell Creek oil field, several iterations of 3-D geomechanical and geological modeling are in progress along with dynamic flow predictive simulation. The first static geological model of the Phase 1 development area (Version 1 model) has been completed along with validation through subsequent history matching and predictive simulation scenarios. The Version 1 geological model has resulted in new interpretations regarding the total porosity, shale volume, effective porosity, permeability, reservoir thickness, and water saturation and has provided a geological framework for predictive simulations. Simulations are currently being conducted to more accurately model CO_2 propagation in the subsurface at discrete time steps to guide monitoring activities and to provide a means of theoretically evaluating various injection scenarios and the relationship between oil recovery and CO_2 storage, which will in turn be validated through monitoring.

Based on the insights gained from the Version 1 model, a second iteration geological model representing the entire field—that is, the Version 2 model—is currently being constructed. The Version 2 model will incorporate new characterization data acquired to minimize data gaps identified by the Version 1 model.

5. Risk assessment

An initial risk assessment was performed by identifying, estimating, and evaluating technical subsurface risks. Technical risks in four primary categories: capacity, injectivity, containment, and seismic were identified and a project-specific risk register was developed. The risks were then analyzed and evaluated in terms of their probability of occurrence and, if they occurred, the potential impact the event would have on the project cost, timing/schedule, scope, and quality. The risks were then mapped according to their probability and impact to the project, and critical risks were identified.

Risk management, modeling, predictive simulation, and MVA are all interrelated processes, where the results of one become the inputs of the others. This creates a dynamic, iterative process that allows the risks to be managed throughout the life of the project. As the project moves forward, it will advance through several phases, e.g., exploratory, preinjection, injection, and postinjection, and the described process will be used to monitor and review the changes to the relevant risks.

6. Monitoring, verification, and accounting

The goal of the MVA program is provide critical data that can be used to verify site security; evaluate reservoir behavior during the injection program; determine interactions between oil, water, and CO_2 within the reservoir; determine the fate of injected CO_2, and investigate mechanisms that affect CO_2 storage efficiency within the EOR process. The MVA program will utilize time-lapse data acquisitions as part of a surface-, near-surface-, and deep-subsurface-monitoring program guided by key 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.

MVA strategies must be compatible with commercial operations and practices (i.e., integrate as much of the operational data as possible into the development of the MVA program) as well as be site-specific, operationally viable, sustainable, and cost-effective. The MVA program will be carried out in a phased approach, in advance of and concurrent to, the phased CO_2 injection plan and will consist of a two-pronged approach to monitor the near surface and subsurface environments. Monitoring technologies being deployed at Bell Creek consist of the following:

- Baseline soil gas concentrations and water chemistries of surface water features and shallow groundwater aquifers are being analyzed to provide information regarding seasonal variations across the range of microenvironments present throughout the field. Time-lapse data will be utilized to determine if a chemical change in these mediums postinjection is a result of natural processes (is within a probable statistical range of naturally occurring levels as determined by preinjection baseline data) or is the result of the injection process or out-of-zone fluid migration.
- Time-lapse pulsed neutron well logs will allow for evaluation of near wellbore fluid saturation changes to evaluate sweep and storage efficiency within the reservoir and to monitor for fluid changes and CO_2 accumulations in overlying formations during and postinjection.
- 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. The VSP data will additionally allow for calibration and enhanced processing of time-lapse 3-D surface seismic data while the permanently installed geophone array will allow for passive seismic monitoring for induced seismicity.
- A tracer flood study (under evaluation) will help to better understand fluid communication pathways during injection and aid in history matching predictive simulations.
- A time-lapse 3-D surface seismic survey is planned over a portion of the baseline 3-D surface seismic survey extent to monitor CO_2 migration between well patterns.
- Surface casing, production casing, flow line, and tubing pressure will be monitored on all active injection and production wells. Additionally, three downhole pressure/temperature gauges and a fiber optic distributed temperature system is deployed in the monitoring and characterization well. Together, the pressure and temperature data will allow understanding of reservoir conditions during injection to better predict fluid behavior and provide key data for history matching.
- Periodic chemical analysis of produced and injected fluids are planned to better understand chemical reactions and the composition of reservoir fluids.

Data acquired through the MVA program will help bound simulation predictions in the context of real-world data. Key parameters will be 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 will in turn allow for decreased uncertainty in predictions, which can be utilized to further target MVA strategies during postinjection. Additionally, MVA data will provide insight into mechanisms that could contribute to premature CO_2 breakthrough during EOR activities, an accurate assessment of long-term site security and storage efficiency, and the ability to predict CO_2 movement and chemical interactions within the reservoir after site closure.

7. Summary

The PCOR Partnership, led by the EERC, is working with Denbury to determine the effect of a large-scale injection of CO_2 into a deep clastic reservoir for the purpose of CO_2 storage in conjunction with EOR at the Bell Creek oil field. A technical team that includes Denbury, the EERC, and others are developing an integrated approach to site characterization, geological modeling, predictive simulation, risk assessment, and monitoring to facilitate assessment of various potential injection schemes, guide monitoring strategies, and determine the ultimate fate of injected CO_2. The iterative process ensures that project economics are optimized and that data are collected at optimal geographic locations and points in the injection time line. Activities during the preinjection and injection phases of the project will ease transition and carry into the closure and postclosure phases and help to design postclosure activities that maximize data value while minimizing project resources. This iterative process also ensures that project economics are optimized by targeting areas of key importance at optimal times and geographic locations.

The Bell Creek project will 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 simultaneous CO_2 EOR and CO_2 storage projects and provide a technical framework for the accounting of CO_2, and 4) the lessons learned and best practices employed can provide the data, information, and knowledge needed to develop similar EOR CO_2 storage projects across the region.

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References

[1] Gorecki CD, Hamling JA, Klapperich RJ, Steadman EN, Harju JA. Integrating CO_2 EOR and CO_2 storage in the Bell Creek oil field. Carbon Management Technology Conference Paper 151476, February 2012.

[2] Encore Acquisition Company. Bell Creek CO_2 project. Internal report, July 2009.

[3] Burt RA, Haddenhorst FA, and Hartford JC. Review of Bell Creek waterflood performance—Powder River, Montana. Society of Petroleum Engineers (SPE) Paper 5670, in *J. of Petroleum Technology*, December 1975.

[4] Rawn-Schatzinger V. Field guide to Muddy Formation outcrop, Cook County, Wyoming. National Insititue for Petroleum and Energy Research, Cooperative Agreement No. FC22-83FE60149, November 1993.