

BELL CREEK TEST SITE – GEOLOGICAL CHARACTERIZATION EXPERIMENTAL DESIGN PACKAGE

Plains CO₂ Reduction (PCOR) Partnership Phase III
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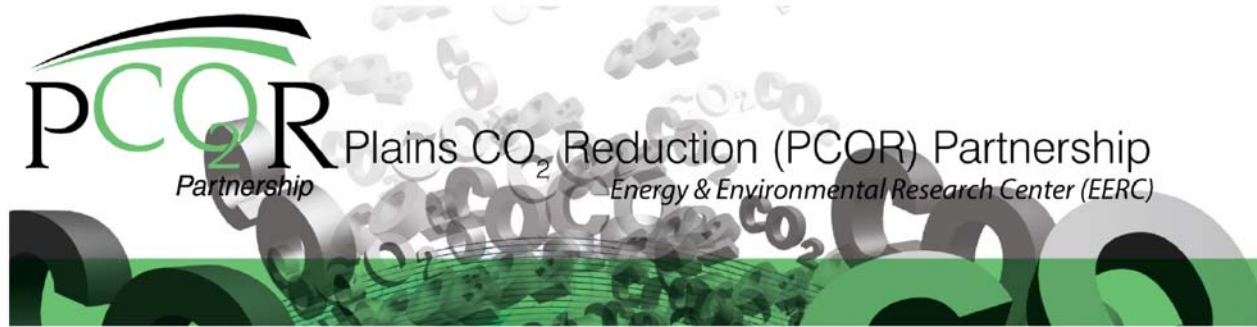
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BELL CREEK TEST SITE – GEOLOGICAL CHARACTERIZATION EXPERIMENTAL DESIGN PACKAGE

FIELD DEMONSTRATION TEST AT BELL CREEK, MONTANA

The Plains CO₂ Reduction (PCOR) Partnership is working with Denbury Onshore LLC (Denbury) to determine the effect of the large-scale injection of carbon dioxide (CO₂) into a deep clastic reservoir for the purpose of simultaneous CO₂ sequestration and enhanced oil recovery (EOR). A technical team that includes Denbury and the Energy & Environmental Research Center (EERC) will conduct a variety of activities to determine the baseline geological characteristics of the injection site and surrounding areas. Denbury will carry out the injection process, while the EERC will conduct CO₂ monitoring, verification, and accounting (MVA) activities at the site. The Bell Creek demonstration project will be a unique opportunity to develop a set of cost-effective MVA protocols for large-scale (>1 million tons per year) CO₂ sequestration in a clastic formation. The baseline geological characterization work that will be conducted over the course of this project will also provide valuable data to support the design and implementation of an injection/production scheme for large-scale CO₂ storage and EOR.

The field demonstration test conducted in the Bell Creek oil field in Powder River County in southeastern Montana will evaluate the potential for CO₂ geological storage and EOR. Since injection will be conducted at the Bell Creek oil field for the simultaneous purposes of EOR and carbon capture and storage (CCS), the project is referred to as the Bell Creek EOR and CCS Project. The CO₂ will be obtained from the Lost Cabin gas-processing plant in central Wyoming. Specifically, Denbury and ConocoPhillips have entered into a 15-year CO₂ purchase-and-sale agreement, and plans are under way to build compression facilities adjacent to the Lost Cabin gas plant to take the CO₂ from 50 to 2200 psi, allowing for delivery to the project site at injection-ready pressure. The CO₂ will then be injected through multiple injection wells into a sandstone reservoir in the Lower Cretaceous age Muddy Formation at a depth of approximately 4500 feet (1372 meters). The plant currently generates approximately 50 million cubic feet of CO₂ per day. The activities at Bell Creek will store an estimated 1.1 million tons of CO₂ annually. The locations of the Bell Creek oil field and Lost Cabin gas plant are shown in Figure 1. A picture of the Lost Cabin gas plant is provided in Figure 2.

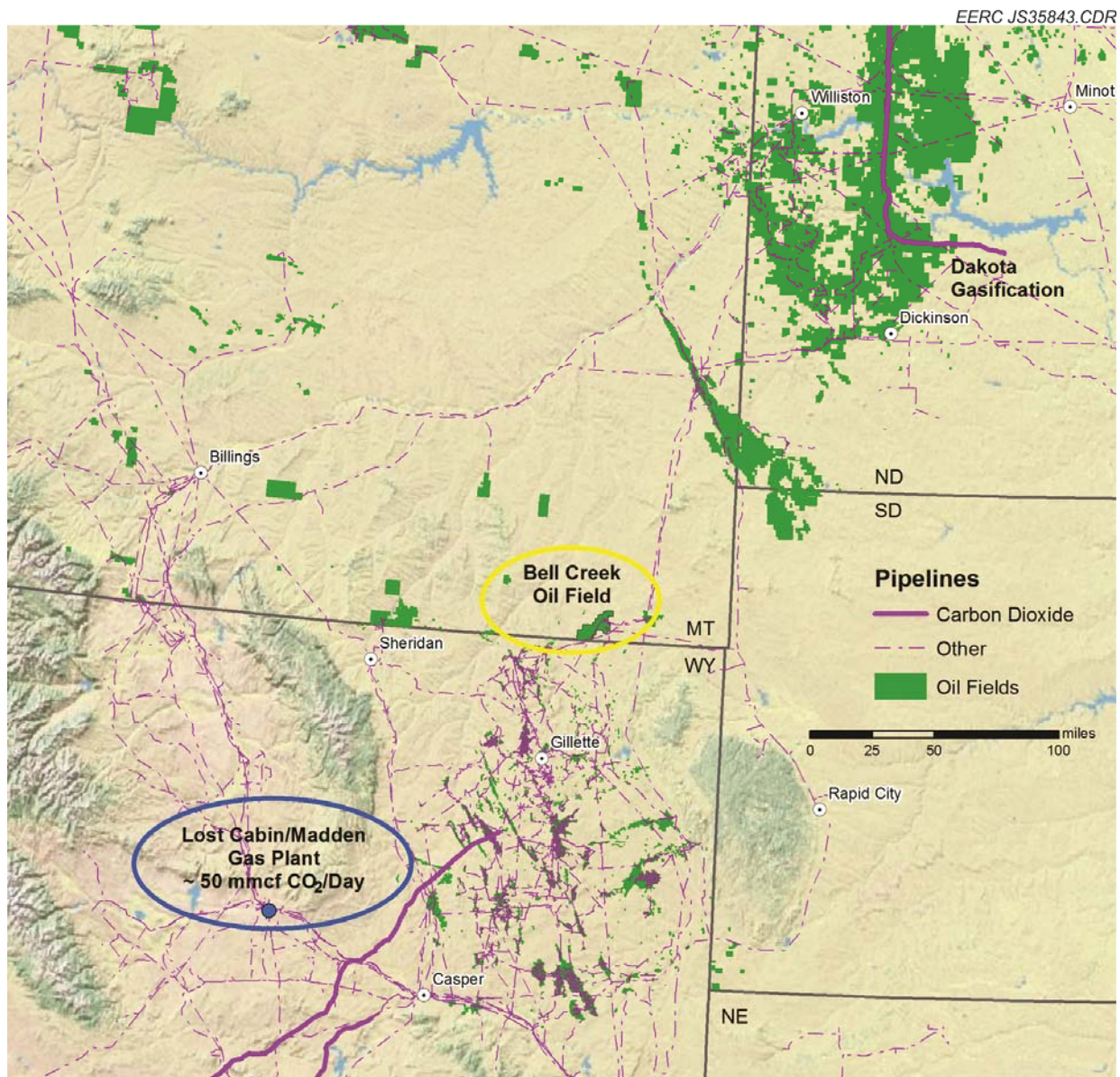


Figure 1. Location of the Lost Cabin gas plant and Bell Creek oil field in Wyoming and Montana.



Figure 2. Lost Cabin gas plant, Wyoming.

BACKGROUND

CCS in geological media has been identified as an important means for reducing anthropogenic greenhouse gas emissions into the atmosphere (Bradshaw and others, 2006). Several means for geological storage of CO₂ are available, including depleted oil and gas reservoirs, deep brine-saturated formations, CO₂ flood EOR operations, and enhanced coalbed methane recovery. The U.S. government is pursuing a vigorous program for demonstration of CCS technology through its Regional Carbon Sequestration Partnership 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 CO₂ injection into geological formations at CCS sites. Regional characterization activities conducted by the PCOR Partnership (Peck and others, 2007) indicate that oil reservoirs represent significant opportunities in North America for both long-term storage of CO₂ and incremental oil production through EOR. The opportunity to cost-effectively store CO₂, 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, will assess the technical and economic feasibility of capturing and storing CO₂ 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 and ConocoPhillips. The 10-year Phase III program proposed by the PCOR Partnership

aims to demonstrate the efficacy of large-scale CO₂ storage in a clastic oil field 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 CO₂. Initial estimates suggest that approximately 15 million tons of CO₂ may be stored in the Bell Creek oil field as a result of EOR activities. 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.
- 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 CO₂-based EOR operations.
- Phase I results indicate that in the PCOR Partnership region at least 3.5 billion tons of CO₂ is needed to produce the incremental oil in the fields that were identified as being suitable for CO₂-based EOR.
- Oil fields generally offer the best opportunities to implement large-scale CO₂ 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 CO₂ capture and transportation through the sale of incrementally produced oil.

Developing cost-effective approaches to predict and determine the fate of the injected CO₂ 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 CO₂ 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. Integrated programs that combine robust geological, hydrogeological, geochemical, and geomechanical characterization activities can generate results that can be used to establish baseline conditions at the site in question. Detailed knowledge of the geological characteristics of a site is then used to develop a cost-effective MVA plan. The baseline conditions subsequently provide a point of comparison to document the movement and fate of the injected gas stream and detect potential leakage from the storage unit. The baseline geological data will also be used to support the design of the CO₂ injection and oil production scheme for the Bell Creek project.

Demonstrating the technical and economic viability of implementing cost-effective risk management and MVA strategies at a large-scale commercial CO₂ EOR project such as the Phase III Bell Creek project will provide stakeholders with the real-world data that are 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 as a carbon management strategy.

PROJECT OBJECTIVES

From the perspective of CCS, the primary project objectives are to demonstrate that 1) CO₂ 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 CO₂; 3) MVA methods can be established to effectively monitor commercial-scale EOR-CO₂ 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 EOR/CO₂ storage projects across the region. A thorough understanding of the geological characteristics of the Bell Creek oil field and its surrounding area is critical to achieve these objectives.

With respect to EOR, the primary objective of the PCOR Partnership at Bell Creek is to provide Denbury with technical support that adds value to its planned operations. The acquisition of baseline geological characterization data as described in this experimental design package will provide Denbury with previously unavailable reservoir data that will support the development of effective injection and production schemes.

SURFACE DESCRIPTION OF THE BELL CREEK OIL FIELD AREA

The Bell Creek oil field is located in a rural upland prairie area. The topography is generally rolling hills, with scattered buttes being the primary distinctive features. Most of the land surface ownership in the Bell Creek area is private, although the area does include large tracts of land owned and managed by the U.S. federal government. Denbury holds a majority of the mineral rights within the Bell Creek oil field and, as the field operator, has the right to inject CO₂ within the boundaries of the oil field for the purpose of EOR operations. The MVA process will serve as a means to monitor the EOR operation and ensure no problems develop with CO₂ migration as the development expands and is implemented. Surface land use activities in the area include oil production, ranching, and small grain farming. Figure 3 is a photograph of the Bell Creek oil field area.

GEOLOGY OF THE BELL CREEK AREA

The Bell Creek oil field in southeastern Montana (Figure 1) lies within the northeastern corner of the Powder River Basin. 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 within which the Bell Creek oil field is located is provided in Figure 4.



Figure 3. Photograph of the Bell Creek oil field in Powder River County, Montana.

Age Units		Rock Formations
Cenozoic	Quaternary	
	Tertiary	Fort Union Fm
Mesozoic	Cretaceous	Fox Hills Fm
		Bearpaw Fm
		Judith River Fm
		Claggett Fm
		Eagle Fm
		Telegraph Creek Fm
		Pierre Fm
		Niobrara Fm
		Carlile Fm
		Greenhorn Fm
		Belle Fourche Fm
		Mowry Fm
		Muddy Fm
		Skull Creek Fm

Figure 4. Stratigraphic column of the northeastern portion of the Powder River Basin. Sealing formations are circled in red, and the primary sink formation is circled in green.

Exploration 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. The Bell Creek oil field is an ideal candidate for a CO₂ tertiary recovery project for a variety of reasons. First, its depth provides adequate temperature and pressure conditions for maintaining injected CO₂ in a supercritical state and supports the maintenance of miscibility or near-miscibility of CO₂ and oil. Also, the high-porosity and permeability conditions of the reservoir allow for high CO₂ injection rates and a fairly rapid production response. Finally, the Bell Creek oil reservoir is overlain by multiple units of thick, competent shales which will serve as seals to prevent vertical migration of CO₂. Hydrocarbon production in the Bell Creek area, in the form of crude oil, is primarily from stratigraphic traps in a Lower Cretaceous age sandstone formation. The formal name of this sandstone formation varies within the literature, with some geologists and regulators referring to it as the “Muddy Formation” and others referring to it as the “Newcastle Formation.” While the two terms are used interchangeably and both have been used to describe the reservoir at Bell Creek, this report and all subsequent project reporting materials will refer to the rock unit as the Muddy Formation. It is anticipated that the clastic reservoirs within the Muddy Formation will be the primary target injection zones for the Bell Creek CCS project.

In the Bell Creek area, the Muddy Formation is dominated by clean sandstones deposited in a near-shore marine environment that have porosity and permeability characteristics that should be adequate for large-scale CO₂ injection. Table 1 provides a summary of several of the key characteristics of the Muddy Formation reservoir that can affect its ability to store CO₂, including depth, thickness, temperature, permeability, salinity, and porosity. Structurally, the Bell Creek oil field is a monocline with a 1° dip to the northwest and whose axis trends southwest to northeast for a distance of approximately 15 miles. 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 sand bodies of the reservoir are dissected and, thus, somewhat compartmentalized by intersecting shale-filled channels. Figure 5 is a map that includes an outline of the Bell Creek oil field, existing wellbores, formation top isopachs, and the locations of shale-filled channels within the unit’s outline. The Bell Creek Field was originally separated into seven distinct operational units (A, B, C, D, E, F, and South Bell Creek Units), which in some cases are at least partially defined by the geometry of the shale-filled channels (Figure 5). The first six of these units were consolidated into the Bell Creek Consolidated (Muddy) Unit by Exxon in late 1991 when it first contemplated implementing five-spot patterns for waterflooding and a future CO₂ injection flood.

The shale formations of the overlying Upper Cretaceous Mowry Formation will provide the primary seal, preventing leakage to overlying underground sources of drinking water (USDW) or the surface. Overlying the Mowry Formation are several low-permeability shale formations, including the Upper Cretaceous age Belle Fourche, Greenhorn, Niobrara, and Pierre Shales, which will provide additional layers of protection from leakage to the surface or USDW.

Table 1. Key Characteristics of the Muddy Formation in the Bell Creek Area

Depth, ft	Thickness, ft	Temperature, °F	Average Permeability, mD	Total Dissolved Solids, ppm	Porosity, %
4300–4500	30–45	108	50–1500	4600–7400	24

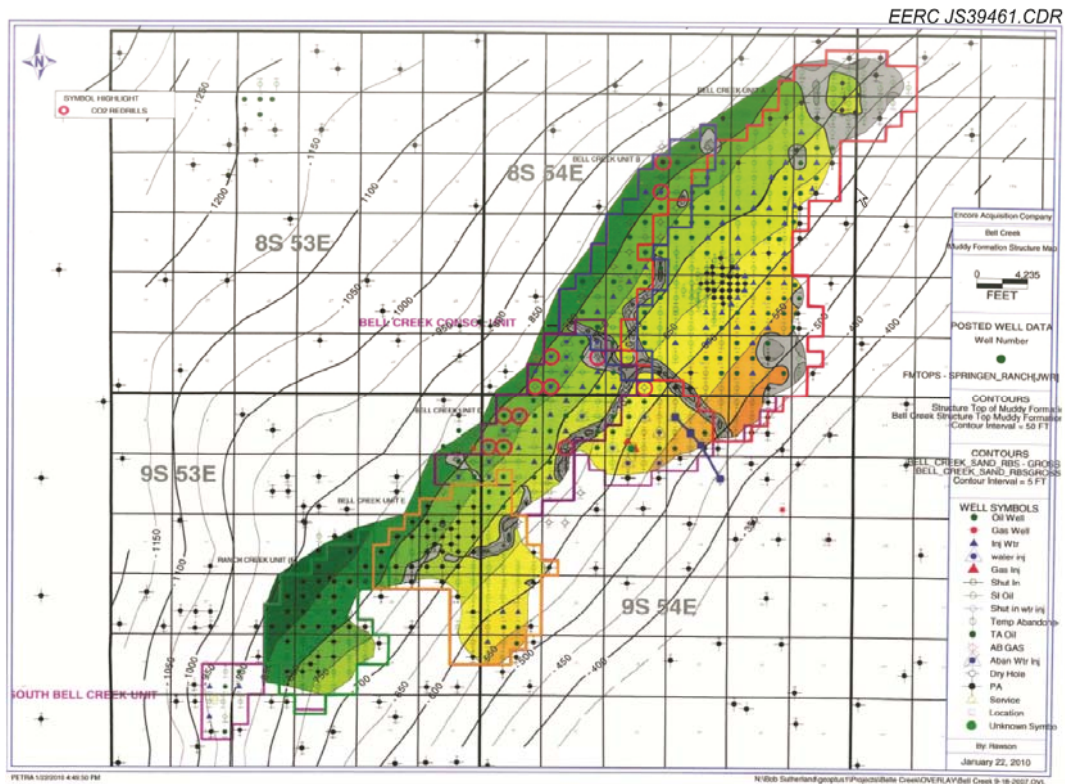


Figure 5. Plan view map of the Bell Creek oil field.

No areas of faulting or fracturing have been identified in the Bell Creek study area. The intermontane nature of the Powder River Basin would suggest there could be faulting and fracturing, but none has been found in the planned injection area.

HISTORY AND CURRENT CONDITIONS OF THE BELL CREEK OIL RESERVOIR

Discovered in 1967, the Bell Creek oil field was considered at the time to be one of the most significant oil discoveries in the Rocky Mountain region, with approximately 353 million barrels of original oil in place (OOIP). The field was aggressively developed, with 450 wells being drilled in the first 2 years after discovery. The rate of oil production from the field reached its peak in August 1968, when it produced approximately 56,000 barrels of oil per day (BOPD). Shortly after reaching its peak, oil production declined rapidly, prompting the initiation of waterflood operations in 1971. The Bell Creek oil field has been operated as a waterflood EOR operation continuously since then, with the current oil production rate being 1041 BOPD. Cumulative production at the end of 2010 was approximately 133 million barrels of oil, which is 38% of the OOIP. Figure 6 is a graph showing the production and injection history of the field.

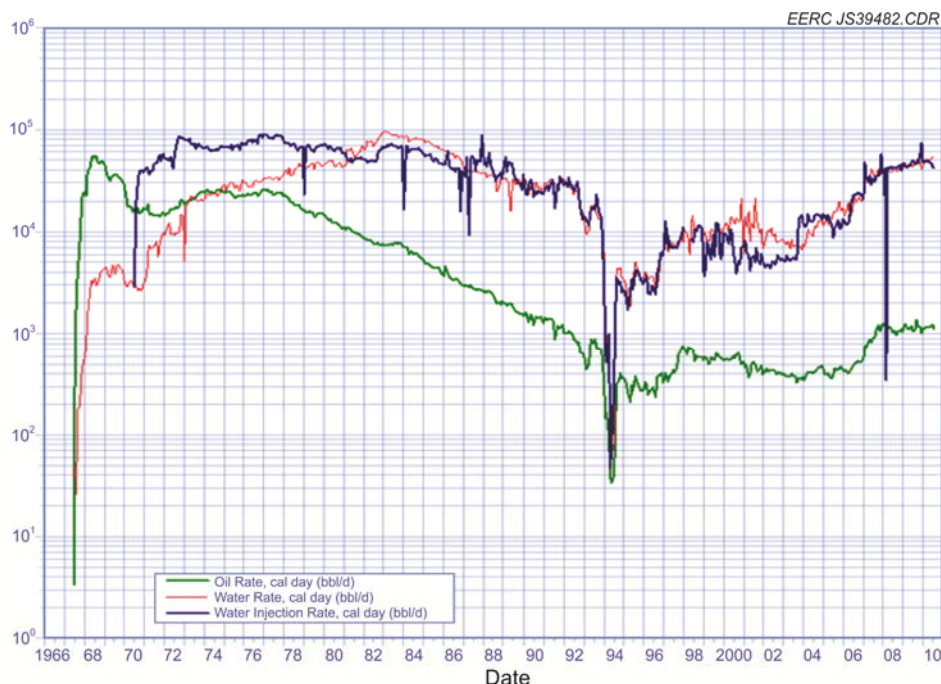


Figure 6. Production and injection history of the Bell Creek oil field.

Covering an area of 21,771 acres, the Bell Creek oil field is organized into one consolidated unit (formerly six separate units designated as A, B, C, D, E, and F) and the separate South Bell Creek Unit, respectively (Figure 7). In recent years, most of the oil production from Bell Creek has been from the former A, B, and D unit areas. Unit A is by far the largest oil reservoir in the Bell Creek Field, with OOIP of over 178 million barrels. As of March 2011, there were 35 wells producing oil and 51 water injection wells in the Bell Creek Field. There is currently a single active water supply well that produces water from the Madison Formation.

A second water supply well is scheduled to be operational by mid-2011. The current reservoir condition measurements indicate a reservoir temperature of 108°F (42°C), having an API gravity of 32°–41°API, as well as an estimated 220 MM barrels of remaining oil in place. Denbury estimates that CO₂ flood operations in the Bell Creek oil field could yield 30+ million incremental barrels of oil over 20 years.

PCOR PARTNERSHIP CHARACTERIZATION ACTIVITIES

The activities, tasks, and deliverables described herein are derived from the PCOR Partnership Phase III Continuation Application Statement of Project Objectives dated September 5, 2007, and information provided by Denbury in October 2010. The overall purpose of the PCOR Partnership characterization activities at the Bell Creek site is to establish the integrity of the Muddy Formation and surrounding shale formations in the Bell Creek area with respect to large-volume CO₂ injection, EOR, and storage.

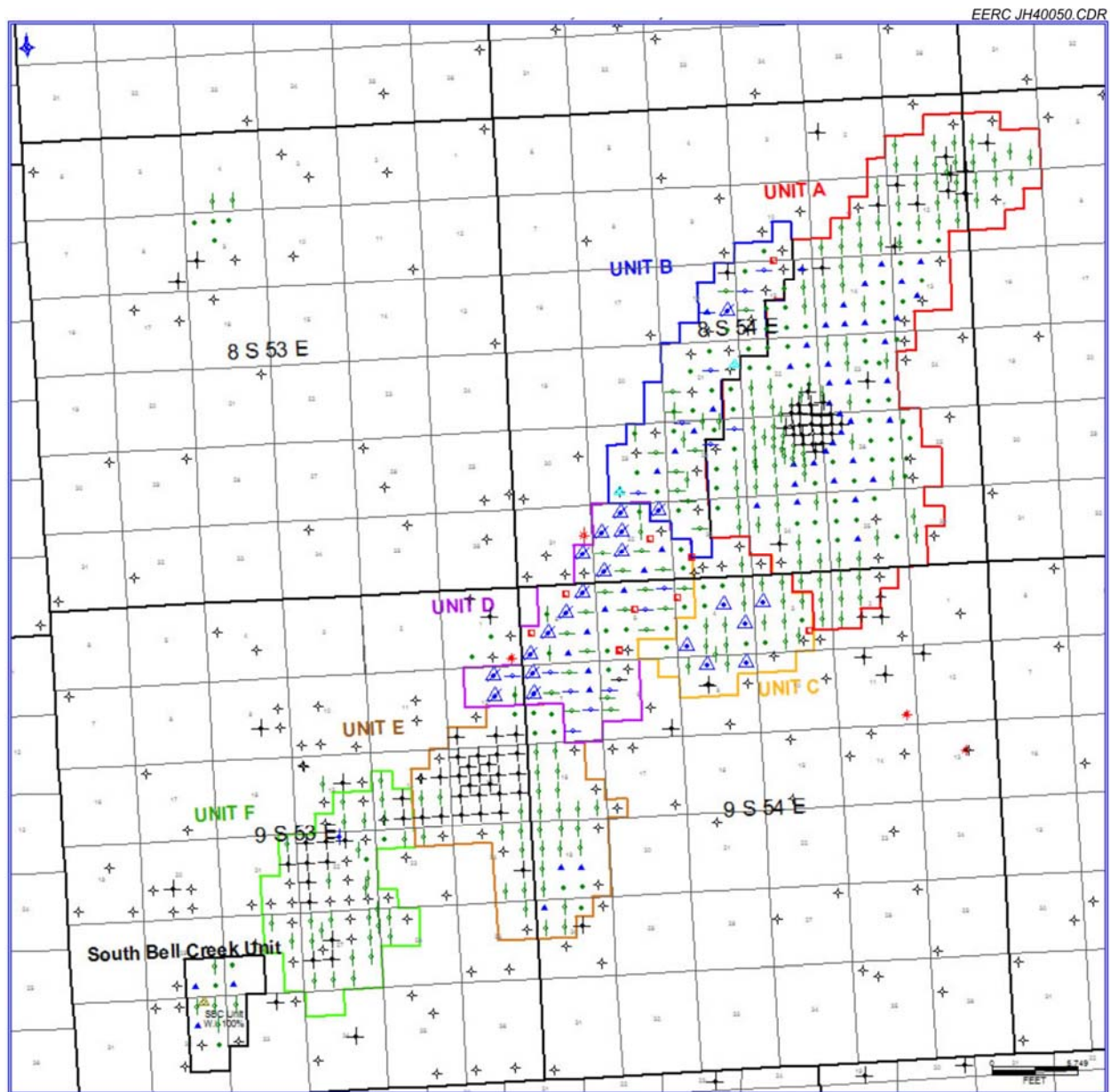


Figure 7. Map of the former Bell Creek oil field Units A, B, C, D, E, and F. The South Bell Creek Unit includes the wells that are located southwest of the F Unit.

This will be accomplished by determining the following:

- Baseline geology
- Rock mineralogy and composition of formation water
- Baseline hydrogeology

- Mechanical rock properties and stress regime
- Nature of geochemical interactions between formation and injected fluids and reservoir rock and cap rock
- Nature of wellbore integrity and leakage potential
- Original and current hydrocarbon volumes and properties

Key characteristics affecting the long-term mobility and fate of the injected CO₂ will be evaluated at three different scales:

- Pool scale (unit of the Bell Creek oil field into which injection will occur)
- Field scale (the entire Bell Creek oil field)
- Regional or subbasin scale (northeastern portion of the Powder River Basin)

Work at the **pool scale** will focus on a phase within a specific area unit of the Bell Creek oil field. It is anticipated that Phase 1 (former Unit D) will be the initial pool targeted for injection. At least seven phases of expansion are anticipated and perhaps more depending on the CO₂ volumes available. Stratigraphic characterization activities at this scale will only include the reservoir and seals directly overlying and underlying the reservoir.

Work at the **field scale** will cover the entire Bell Creek oil field. Stratigraphically, the entire sedimentary succession from the basement to the surface will be evaluated at the local scale.

Work at the **regional**, or **subbasin scale**, will evaluate relevant data and information on key geological formations over the northeastern portion of the Powder River Basin. Hydrogeological systems and the regional continuity of key sealing formations will be the focus of studies at this large scale.

EXISTING DATA RECONNAISSANCE, ACQUISITION, AND INTEGRATION

Denbury will provide the PCOR Partnership with many of the basic data sets upon which baseline characteristics will be established. The following data sets will be examined for information regarding local and regional geological properties:

- Well/reservoir information of the pertinent formations.
- Data on drilling, completion, and stimulation/workover of key wells in the area.
- Digital production/injection history of key wells.

- Geological and geophysical information on the key formations in the Bell Creek area, including formation isopach and depth maps, interpreted seismic data, hydrogeological characteristics, etc.
- Reservoir engineering data on injection zone characterization and CO₂ injection/monitoring schemes.

BASELINE RESERVOIR AND SURFACE CHARACTERIZATION

The primary purposes of PCOR Partnership monitoring activities at the Bell Creek oil field are 1) early detection of any migration of CO₂ outside of the target injection zone and 2) collection of data to support predictions of plume migration and fate. These activities will support both the EOR and CCS components of the project. From an EOR standpoint, careful monitoring will provide the operator with valuable information regarding sweep efficiency and the optimization of the overall injection and production scheme. With respect to CCS, monitoring data will be essential to ensure stakeholders that the injected CO₂ will remain in the intended target storage zone during and after injection operations. Effective monitoring requires thorough knowledge of the baseline conditions of the areas within the geosphere that will be monitored. The portions of the geosphere in the Bell Creek oil field area that will be evaluated by the PCOR Partnership include the Muddy Formation, which will serve as the target reservoir; the overlying Mowry Formation, which will serve as the primary seal; the rocks of the Fox Hills, Hell Creek, and Fort Union Formations, which have been classified as potential USDW; near-surface soil; and surface water bodies. The following is a list of the types of baseline characterization data that will be collected between November 2010 and December 2012 and the specific monitoring purpose to which those data can be applied:

- To establish baseline pressure, temperature, and geochemistry conditions for monitoring CO₂ plume movement:
 - Reservoir pressure and temperature data
 - Pressure and temperature data from overlying formations
 - Geochemical analyses of fluids (water, gas, oil) collected at the wellhead
 - Geochemical analyses of fluids (water, gas, oil) collected from the Muddy Formation reservoir
 - Geochemical analyses of fluids (water, gas) collected from overlying formations
 - 3-D seismic survey data
- To provide early warning of CO₂ migration outside of the storage reservoir:
 - Injection well pressure data
 - Reservoir pressure data
 - Pressure data from overlying formations
 - Geochemical analyses of Muddy Formation reservoir fluids (water, gas, oil) taken from wells in areas adjacent to the injection zone
 - Geochemical analyses of fluids (water, gas) from overlying formations

- To establish baseline CO₂ concentrations at the ground surface:
 - Soil vapor sampling and analyses for CO₂
 - Soil vapor sampling and analyses for natural and/or introduced tracers
 - Surface water sampling and analyses for CO₂, natural and/or introduced tracers, standard water quality parameters, and metals from nearby ponds and streams

In addition to the collection of data described above, baseline characterization activities will also be focused on determining baseline geological conditions in the Bell Creek area with respect to the following general aspects of the site that can significantly affect reservoir injectivity, capacity, and integrity:

- To identify preexisting faults and/or fracture systems, if any
 - Historical and new well geophysical logging data
 - Historical and new seismic survey data (four 2-D seismic lines exist)
- To determine the integrity of the cap rock
 - Geomechanical testing of Mowry Shale core samples
 - Geochemical testing of Mowry Shale core and/or cuttings samples
- To evaluate wellbore integrity issues
 - Historical and new cement bond logs
 - Historical and new mechanical integrity testing data
- To understand the mineralogy and geochemistry of sink and seal formations
 - Laboratory analyses of core and/or cuttings samples
 - Laboratory experiments to evaluate interactions between CO₂, reservoir fluids, and rocks of the Muddy and Mowry Formations under reservoir temperature and pressure conditions

BASELINE GEOLOGIC MODELING

At the pool and field scales, a geological model of the strata associated with the Lower and Middle Cretaceous clastic formations will be created to evaluate reservoir geometry and internal architecture. The overlying/surrounding cap rock will also be evaluated, as well as the associated aquifer systems that may provide reservoir support in places. Information about the geology of the injection zone and confining strata (e.g., structural setting, stratigraphy, general lithology, thickness, and areal extent) will be collected, processed, and interpreted for the local-scale area.

At the regional scale, the geology, stratigraphy, and lithology will be evaluated, delineated, and described for the entire sedimentary succession from the base of the Lower Cretaceous (lower confining unit) to the surface (Upper Cretaceous/Lower Paleocene Montana Group and Quaternary drift) for the northeastern Powder River Basin (Figure 4). In addition, the structural elements in the area, from the basement to the surface, will be investigated to identify any faults and/or fractures that would allow migration of reservoir and injected fluids.

ROCK MINERALOGY AND FORMATION WATER CHEMISTRY

Rock mineralogy and the composition of injection zone fluids are important for determining potential geochemical reactions between the injected CO₂ and injection formation fluids and rocks that may affect the integrity of the injection site.

Laboratory tests will be conducted on core samples to assess the geochemical reactions between the injected CO₂ and the rocks and fluids of the reservoir and seal. It is anticipated that core from a portion of the seal, transitional zone, and reservoir rock will be obtained and used for mineralogy and other testing. The results will provide data regarding 1) potential mineralization that may occur and 2) the partitioning of CO₂ between oil, formation waters, and rocks (reservoir and seal).

BASELINE HYDROGEOLOGY

Identifying and characterizing the hydrogeological regime at a CO₂ injection site is important to understand possible migration pathways and the effect the flow of formation water may have on the spread of the injected CO₂. The following hydrogeological information will be collected for key hydrostratigraphic units at both local and regional scales:

- Hydrostratigraphic delineation
- Aquifer and aquitard geometry and thickness
- Rock properties relevant to the flow of formation waters and injected CO₂ such as porosity and absolute and relative permeability
- Geothermal regime
- Pressure regime
- Direction and strength of formation water flow

A model of the flow-driving processes and mechanisms in the region and strata of interest will be developed that will help in understanding the effect of natural flow on flow paths in the Lower Cretaceous age interval and outside, in case of leakage, and also of the effect of injection on the system.

GEOCHEMICAL MODELING

The goal of this activity is to model the interaction between the injected CO₂, the reservoir fluids, and the rocks to determine 1) the potential amount of CO₂ that may be stored through mineral precipitation and 2) the effects of mineral precipitation on permeability and injectivity. A mineralogical assessment of core samples will be performed to predict the amounts and nature of

mineral trapping of the injected CO₂. Mineral compositions will be obtained using an electron microprobe. Powdered core samples will be analyzed by scanning electron microscopy techniques, x-ray diffraction (XRD), and x-ray fluorescence. The compositional data will be used to perform geochemical modeling to assess the long-term fate of CO₂ in the subsurface.

GEOMECHANICAL PROPERTIES AND STRESS REGIME

The goal of this activity is to establish the geomechanical properties of the reservoir and cap rock and the stress regime in the area to assess the mechanical integrity of the system and potential for rock fracturing. An in-depth review of the stress regime and structural features in the area of the reservoir will be conducted to identify structures such as faults or fractures. This information will help to elucidate the geological history of the reservoir and identify possible natural leakage paths. Project activities may include in situ stress orientation and magnitude analysis, including log-based analysis of rock mechanical properties and geomechanical modeling.

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