BELL CREEK TEST SITE – GEOMECHANICAL EXPERIMENTAL DESIGN PACKAGE

Plains CO_2 Reduction (PCOR) Partnership Phase III
Task 4 – Deliverable D87

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

BELL CREEK TEST SITE – GEOMECHANICAL EXPERIMENTAL DESIGN PACKAGE

INTRODUCTION

The Plains CO_2 Reduction (PCOR) Partnership is working with Denbury Onshore LLC to evaluate the efficacy of developing a robust and practical monitoring, verification, and accounting (MVA), risk management, and simulation project associated with commercial-scale injection of carbon dioxide (CO_2) for the purpose of simultaneous enhanced oil recovery (EOR) and storage of CO_2. A technical team that includes Denbury and the Energy & Environmental Research Center (EERC) will conduct a variety of activities to 1) determine the geomechanical properties of the target injection formation and key sealing formations in the vicinity of the injection site and 2) model the effects that large-scale injection of CO_2 may have on those properties. Denbury will carry out the injection process, while the EERC will conduct CO_2 MVA activities at the site. Geomechanical characterization efforts will be designed to confirm the mechanical integrity of the system and are, therefore, considered to be critical elements of the MVA program. The Bell Creek demonstration project will be a significant opportunity to develop a set of cost-effective MVA protocols for large-scale (>1 million tons a year) CO_2 storage associated with an EOR operation. The effectiveness of the MVA activities will be at least partially dependent on developing a thorough understanding of the geomechanical properties of the site.

The field demonstration test conducted in the Bell Creek area of Powder River County, Montana, will evaluate the potential for CO_2 geological sequestration and EOR. 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 owned and operated by ConocoPhillips. The plant currently generates approximately 50 million cubic feet of CO_2 per day (Figure 1). The activities at Bell Creek will sequester an estimated 1.1 million tons of CO_2 annually.

This report comprises the current plan with respect to the geomechanical testing for the Bell Creek project. As more data are gathered, it is anticipated that the actual geomechanical testing will be adjusted to better fit site-specific characteristics and evolving project needs.

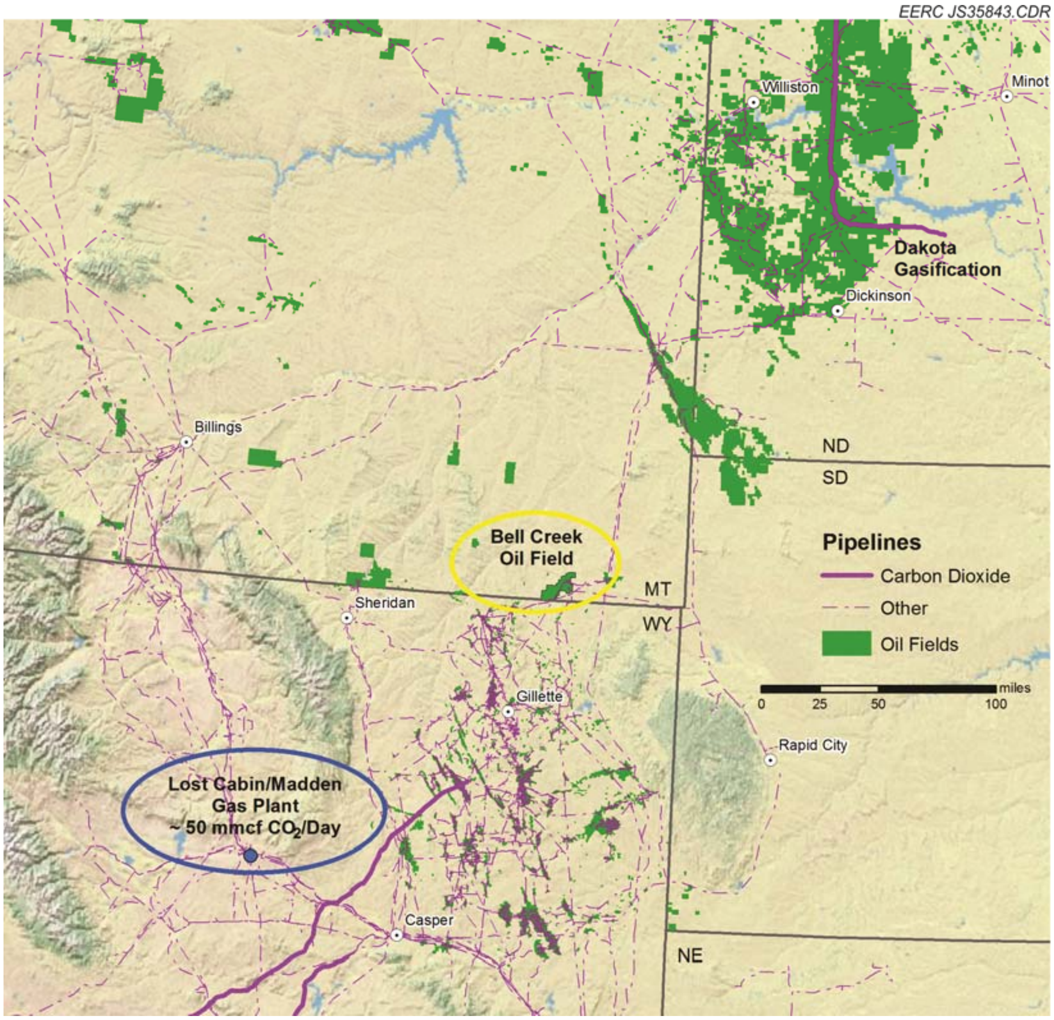

Figure 1. Location of the Lost Cabin gas plant and Bell Creek oil field in Wyoming and Montana. The PCOR Partnership Phase III Bell Creek project will be conducted within the Powder River Basin in southeastern Montana.

BACKGROUND

CO_2 capture and storage (CCS) in geological media have been identified as important means for reducing anthropogenic greenhouse gas emissions into the atmosphere (Bradshaw and others, 2006). Several means for geological storage of CO_2 are available, such as depleted oil and gas reservoirs, deep brine-saturated formations (often referred to in literature as "saline formations"), CO_2 flood EOR operations, and enhanced coalbed methane recovery. Regional characterization activities conducted by the PCOR Partnership (Peck and others, 2007) indicate that oil reservoirs represent the near-term major opportunities for geologic storage of CO_2 in North America.

Projects focused on CCS and associated MVA have been, and continue to be, conducted to evaluate the technical and economic components of CCS technology and provide a basis for scale-up to large demonstrations such as those being undertaken as part of the PCOR Partnership Phase III program. Developing cost-effective approaches to predict and determine the fate of the injected CO_2 is an important aspect of the emerging CCS technology. MVA activities are critical components of geological storage locations for two key reasons. First, the public must be assured that CO_2 geological storage is a safe operation. Second, markets need assurance that credits are properly assigned, traded, and accounted for. Integrated core-sampling and geomechanical analysis programs can generate results that can be used to establish baseline conditions at the site in question. The baseline conditions subsequently provide a point of comparison to predict and document the effects of the large-scale CO_2 injection on the geomechanical integrity of both the target injection formation and its overlying seal. The results of laboratory-based geomechanical evaluations coupled with robust geomechanical modeling based on those results can guide the development of injection schemes that maximize the efficiency of injection and MVA plans that minimize the risks of leakage.

The U.S. government 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 fiscal years (October 2007 to September 2016), and its main focus is characterization and monitoring of large-scale CO_2 injection into geological formations at CCS sites.

As one of the seven RCSPs, the PCOR Partnership, covering nine U.S. states and four Canadian provinces, is assessing the technical and economic feasibility of capturing and storing (sequestering) CO_2 emissions from stationary sources in the central interior of North America. The partnership is composed of numerous private and public sector groups from nine states and four provinces.

The 10-year Phase III program proposed by the PCOR Partnership aims to demonstrate the efficacy of large-scale CO_2 sequestration in two locations, including the Bell Creek CCS project being planned by Denbury (Figure 2). It is anticipated that the results generated at the Bell Creek site will provide insight and knowledge that can be directly and readily applied throughout the world. The geomechanical characterization activities described in this document are scheduled to be conducted over the course of 2010 to 2012, with a final report describing the results of these activities due January 31, 2013.

BELL CREEK CCS PLAN OVERVIEW

Carbon dioxide will be obtained from ConocoPhillips' Lost Cabin gas plant (Figure 3), a gas-processing facility located in Fremont County, Wyoming. Denbury and ConocoPhillips have entered into a CO_2 offtake agreement, and plans are under way to build compression facilities adjacent to the Lost Cabin gas plant to take the CO_2 from approximately 50 to 2200 psi, allowing for delivery to the project site at injection-ready pressure. The project, which will be

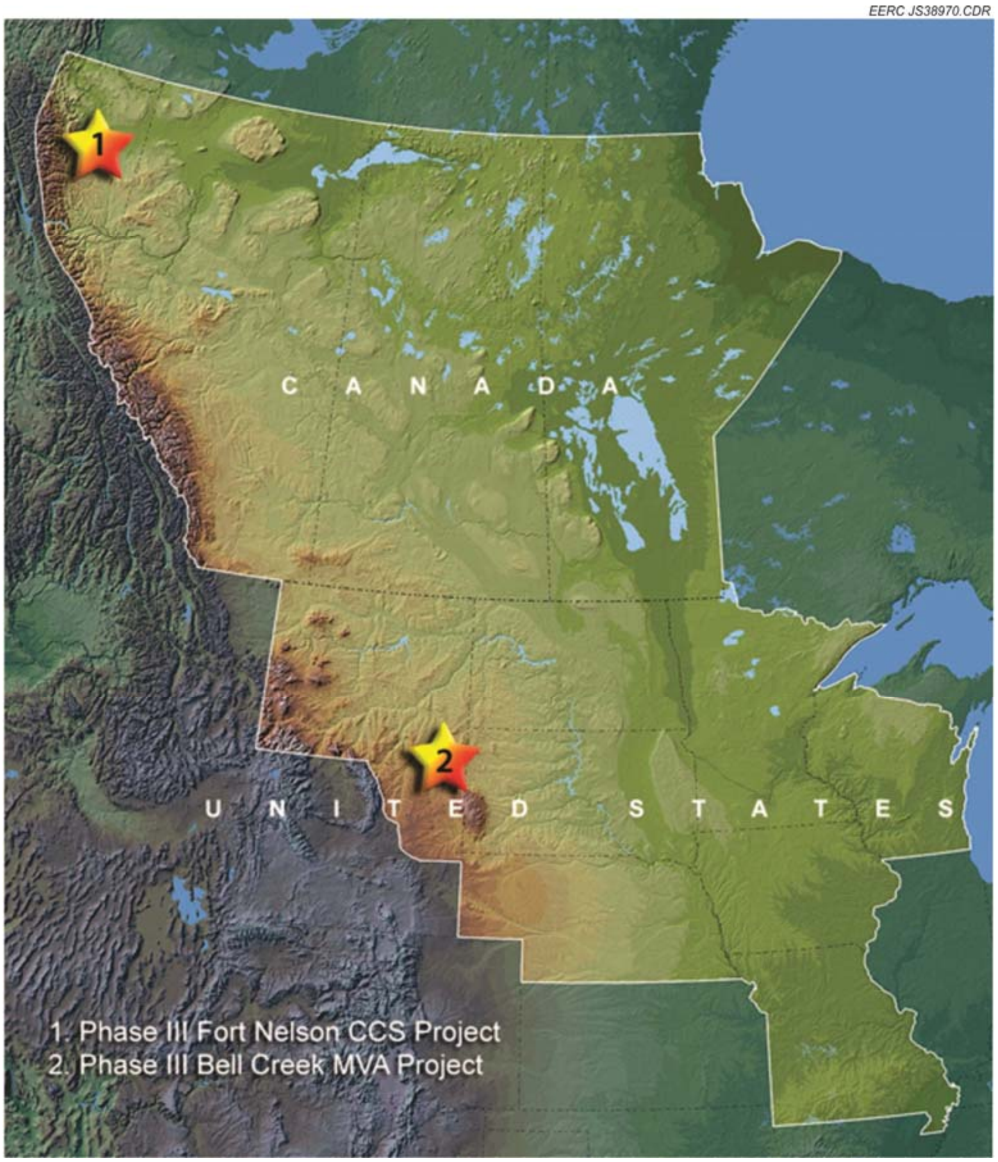

Figure 2. Location of Phase III sites in the PCOR Partnership region.

conducted in the Bell Creek oil field in Powder River County, will provide insight regarding the impact of miscible or near-miscible CO_2 flood tertiary recovery on oil production and successful CO_2 storage within a sandstone reservoir in the Cretaceous age Muddy (Newcastle) Formation.

GEOLOGY OF THE BELL CREEK AREA

The Bell Creek area in southeastern Montana (Figure 1) lies within the northeastern corner of the Powder River Basin (Figure 2). The sedimentary succession in the Bell Creek area consists

Figure 3. Lost Cabin gas plant, Lysite, Wyoming.

of, in ascending order, Jurassic gypsum, sandstones, and shales; Upper and Lower Cretaceous sandstones, shales and carbonates; and Tertiary consolidated and unconsolidated clastic sediments (Figure 4).

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 CO_2 tertiary recovery project because its depth provides adequate temperature and pressure conditions for maintaining injected CO_2 in a supercritical state and supports miscibility or near miscibility of the CO_2 in the oil. The high porosity and permeability conditions allow for high CO_2 injection rates and a fairly rapid production response. Hydrocarbon production in the Bell Creek area, in the form of crude oil, is primarily from stratigraphic traps in the Early Cretaceous age Muddy (Newcastle) Formation. Three-dimensional seismic may help define the updip limit of the reservoir. It is anticipated that the clastic reservoirs within the Muddy (Newcastle) Formation will be the primary target injection zones for the Bell Creek CCS project. The geomechanical properties of this formation will need to be determined.

The Mowry Shale, Muddy (Newcastle) Formation, and Skull Creek Shale are all part of the Lower Cretaceous age statigraphy. This section is composed of a succession of gray shales, which occasionally contain bentonite layers and brown to yellow and white sandstones.

In the Bell Creek area, the Muddy (Newcastle) Formation is dominated by clean sandstones with prominent barrier island structures that have porosity and permeability

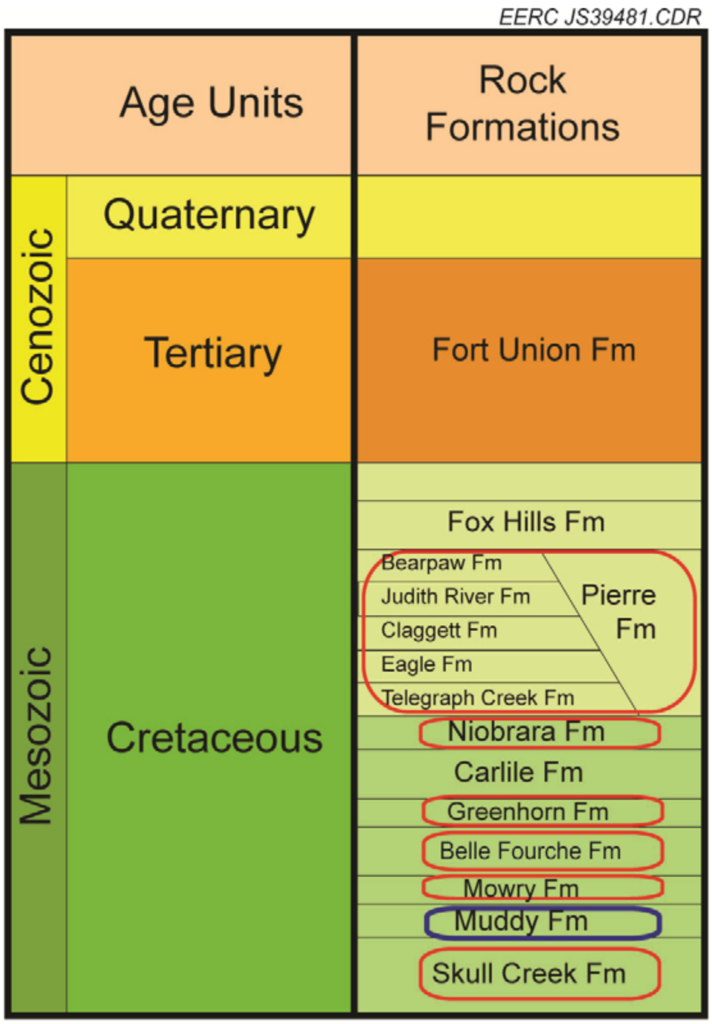

Figure 4. Stratigraphic column of the Powder River Basin, Montana (Montana Bureau of Mines and Geology, 2007).

characteristics that may be adequate for large-scale CO_2 injection. Currently existing data indicate that the Muddy (Newcastle) Formation ranges between 20 and 30 ft in thickness in the Bell Creek area, with porosity averaging 24% and permeability as high as 1500 mD. Table 1 summarizes the currently available data regarding key characteristics of the Muddy (Newcastle) Formation.

Table 1. Anticipated Key Characteristics of the Likely Target Injection Formation in the Bell Creek Area

Formation	Depth, ft	Thickness, ft	Maximum Permeability, mD	Minimum Permeability, mD	Porosity, avg %
Muddy (Newcastle)	4300–4500	30–45	1500	50	24

With respect to seals that will prevent upward migration of the injected CO_2, shale formations of the overlying Upper Cretaceous Mowry Formation will provide the primary seal with respect to preventing leakage to the surface. Overlying the Mowry Formation is the Upper Cretaceous age Belle Fourche, which would provide yet another layer of protection from leakage to the surface. It is anticipated that key geomechanical properties of the Mowry Shale will be determined.

CURRENT ESTIMATED CONDITIONS

Currently there are 35 active producers and 51 active water injection wells in the field. Ultimately, on full-field 80-acre 5-spot pattern development, there will be 164 individual 5-spot patterns comprising approximately 203 active producers and 238 active water injection wells. Current reservoir temperature is 108°F (42°C). Oil API gravities range from 32° to 41°API (northeast to southwest) across the field. An estimated 220 MM barrels of remaining oil in place is available for future tertiary recovery operations. Denbury's proposed future tertiary program for Bell Creek is described in the Work Plan section of this document.

WORK PLAN

Plans for drilling activities include the collection of core and cuttings from the key sink and seal formations. It is anticipated that the laboratory-based geomechanical work will be conducted using core from the Bell Creek area. 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 thus far. The overall purpose of these activities, from the perspective of the PCOR Partnership, is to create a best practices manual that outlines a set of guidelines for MVA operations at a location that is annually injecting over 1 million tons of CO_2 into a clastic formation for long-term sequestration and EOR.

The goal of the geomechanical characterization program is to assess the geomechanical properties of the key sink and seal formations, the stress regime in the area, and the mechanical integrity and fracture pressure of the system, which is expected to exceed normal operating conditions. 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 like faults. It is anticipated that project activities will include a variety of laboratory- and field-based investigations. Laboratory-based activities will include compression tests to determine rock strength, static and dynamic elastic properties, compressibility, and stress-dependent permeability. Field-based activities may include in situ stress orientation and magnitude analysis, including log-based analysis of rock mechanical properties. The results generated by the laboratory and field investigations will provide the basis for geomechanical modeling.

EXISTING DATA RECONNAISSANCE, ACQUISITION, AND INTEGRATION

It is anticipated that Denbury will provide the PCOR Partnership with many of the basic, raw data sets upon which baseline characteristics will be established. The following data sets will be examined for information regarding local and regional stress regimes and geomechanical 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, the presence and orientation of fractures and/or faults, and other data that may provide insight into the geomechanical properties and integrity of the key sink and seal formations. Currently four (4) seismic lines exist, one of which is from the U.S. Geological Survey (USGS) and is interpreted.

- Reservoir engineering data on injection zone characterization and CO_2 injection/ monitoring schemes.

LABORATORY-BASED GEOMECHANICAL INVESTIGATIONS

It is anticipated that existing warehouse core from Bell Creek wells will be available for review and limited testing as early as the spring or summer of 2011. Sets of 1.5-inch-diameter core samples representing the cap rock and reservoir from the Bell Creek CCS site will be requested from the USGS Core Library in Denver, Colorado. If permitted, samples will be tested for bulk density, acoustic velocity, uniaxial strength, and triaxial strength. Peak strength (at failure) and elastic properties that will be measured will include, but are not necessarily limited to, confining stress at failure, peak strength, Young's modulus, Poisson's ratio, bulk modulus, and shear modulus. Selected samples may also be tested for residual friction measurements.

In these investigations, samples will be fitted with strain gauges at 90° intervals around the core to measure the deformation observed under load. Multiple tests for various loading regimes will be carried out to define the mentioned properties. The tests will also serve for finding the parameters for several common failure criteria. These criteria are then used to predict the stress state at which failure would occur in rock. Further, the predicted values aid in determining the pore pressure buildup which can be sustained by rock without failure. The parameters for Hoek-Brown and Mohr-Coulomb criteria may also be found in the study. A brief description of these criteria follows.

The Hoek-Brown criterion is an empirical 2-D criterion, which sets limitations on major and minor principal stresses. The criterion is given by the following relationship:

$$\sigma_1 = \sigma_3 + \sqrt{m\sigma_c\sigma_3 + s\sigma_c^2} \quad \text{[Eq. 1]}$$

where σ_1 and σ_3 are major and minor principal stresses, σ_c is the uniaxial compressive strength of the rock, and *m* and *s* are constants. Stresses σ_1 and σ_3 are defined by the pressure of overburden and tectonic forces, while σ_c and constants *m* and *s* are determined in laboratory tests.

The Mohr-Coulomb criterion also sets limitations on σ_1 and σ_3 by utilizing the concept of cohesion *c* and the angle of internal friction ϕ. It is given by the following formula:

$$\sigma_1 - \sigma_3 = \frac{2(c + \mu\sigma_3)}{\sqrt{\mu^2 + 1} + \mu} \quad \text{[Eq. 2]}$$

Here $\mu = \tan\phi$ is the coefficient of friction.

Other parameters, such as uniaxial tensile strength, will also be obtained in case the use of additional failure criteria is desirable. These parameters are derived in the laboratory tests at the moment when failure of the tested sample occurs. However, degradation of the rock material starts prior to failure and should be avoided in the course of injection, if possible. In the planned study, techniques specifically measuring the acoustic wave amplitude may be employed to determine the beginning of the degradation process. Potentially, these data can be used for setting limiting conditions on the pressure buildup in the reservoir.

The Hock-Brown and Mohr-Coulomb criteria provide useful estimates in cases where the stress tensor is known. However, the stress tensor can be measured only at discrete points within the system. Alternatively, it can be estimated analytically. Both measured and analytically estimated stresses will vary significantly within the structure. Depending on the shape of the zone of porosity, which may be a stream channel, the existence of areas of stress concentrations may be possible. These areas are most susceptible to failure. To check for the possibility of the existence of such areas, numerical modeling accounting for the geometry of the system will be run. Calculating stresses at different points within the system requires knowledge of elastic properties, Young's modulus and Poisson's ratio, of rock. Thus it is anticipated that a set of tests to derive these parameters will be run. The tests will assess two values of the parameters: one distinct in a static process (a process with no or slow development in time) and one that is distinct in the case of dynamic processes (a fast-developing process, e.g., fracturing of rock or an earthquake). These data can also be used for geophysical log calibration and have potential implications to MVA.

The results of these core analyses will provide a basis for developing accurate models that can be used to predict the effects that large-scale CO_2 injection can have on reservoir and cap rock.

SUMMARY

It is anticipated that the results of the geomechanical characterization activities described above will indicate that both reservoir and cap rock at the Bell Creek CCS project site have sufficiently high mechanical strength to allow for the safe and effective injection of over 1 million tons a year of CO_2. It is hoped that results will show these rocks can sustain high stresses without experiencing significant deformations and that failure of the cap rock should not occur under normal operating conditions.

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