PLAINS CO_2 REDUCTION (PCOR) PARTNERSHIP (PHASE III) – WILLISTON BASIN FIELD DEMONSTRATION SITE

Geomechanical Experimental Design Package – D30

(For the period October 1, 2007, through September 30, 2009)

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TABLE OF CONTENTS

LIST OF FIGURES

PLAINS CO_2 REDUCTION (PCOR) PARTNERSHIP (PHASE III) – FIELD DEMONSTRATION TEST AT FORT NELSON, BRITISH COLUMBIA, GEOMECHANICAL EXPERIMENTAL DESIGN PACKAGE – D38

The PCOR Partnership team at the Energy & Environmental Research Center (EERC) is working with several PCOR Partnership Partners to determine the effect of the large-scale injection of carbon dioxide (CO_2) into a carbonate reservoir of an oil field in the Williston Basin for the purpose of simultaneous enhanced oil recovery (EOR) and CO_2 sequestration. The technical team, led by the 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. An oil production company that is a member of the PCOR Partnership will carry out the injection process, while the EERC will conduct CO_2 monitoring, mitigation, and verification (MMV) activities at the site. The geomechanical characterization efforts will be designed to confirm the mechanical integrity of the system and are, therefore, considered to be critical elements of the MMV program. The Williston Basin demonstration project will be a unique opportunity to develop a set of cost-effective MMV protocols for large-scale (>0.5 million tons a year) CO_2 sequestration in a carbonate oil reservoir. The effectiveness of the MMV 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 Williston Basin will evaluate the potential for geological sequestration of CO_2 as part of a commercial EOR project. It is anticipated that the depth of the reservoir, which will be in carbonate rocks, will be greater than 8500 ft, which is substantially deeper than previous CO_2 flood EOR projects in carbonate reservoirs. The results of the Phase III Williston Basin activities will provide insight regarding the impact of CO_2 under deep reservoir pressure and temperature conditions on sink integrity (i.e., seal degradation), MMV, and successful sequestration within a carbonate oil reservoir. The CO_2 will be obtained from the Antelope Valley Station coal-fired power plant in central North Dakota and injected into an oil reservoir in a Paleozoic-age carbonate formation at a depth of approximately 8500 ft to 10,000 ft.

BACKGROUND

General

CO_2 capture and storage (CCS) in geological media has been identified as an important means for reducing anthropogenic greenhouse gas emissions into the atmosphere (Bradshaw et.

al, 2006). One of the PCOR Partnership's main goals is to identify and test CCS opportunities in the central interior of North America. 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 aquifers"), CO_2 flood EOR operations, and enhanced coalbed methane recovery. Regional characterization activities conducted by the PCOR Partnership (Peck et al., 2007; Smith et al., 2005) indicate that oil fields represent the second largest-volume opportunity for long-term storage of CO_2 in North America, with the PCOR Partnership region having over 1 billion tons of CO_2 storage capacity in oil fields suitable for EOR. In an effort to significantly reduce CO_2 emissions from the operation of a coal-fired power plant in central North Dakota (Figure 1) and to incrementally increase the productivity of an oil reservoir in western North Dakota, Basin Electric Power Cooperative is taking steps to capture approximately 1 million tons/year of CO_2 from its Antelope Valley Station coal-fired power plant. The source and sink for this CCS project are both located in the North Dakota portion of the Williston Basin (Figure 1), and the project is, therefore, referred to as the Williston Basin CCS Project.

Projects focused on CCS and associated MMV have been, and continue to be, conducted in the United States and Canada 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. MMV 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 MMV plans that minimize risks of leakage.

The U.S. government is pursuing a vigorous program for demonstration of this technology through its Regional Carbon Sequestration Partnership Program, which entered Phase III in October 2007. This phase is planned for a duration of 10 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. The geomechanical characterization activities described in this document are scheduled to be conducted over the course of 2008 and 2009, with a final report describing the results of these activities due April 30, 2010.

The PCOR Partnership, covering nine U.S. states and four Canadian provinces, will assess 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 comprises more than 80 private and public sector groups. The 10-year Phase III program aims to demonstrate the

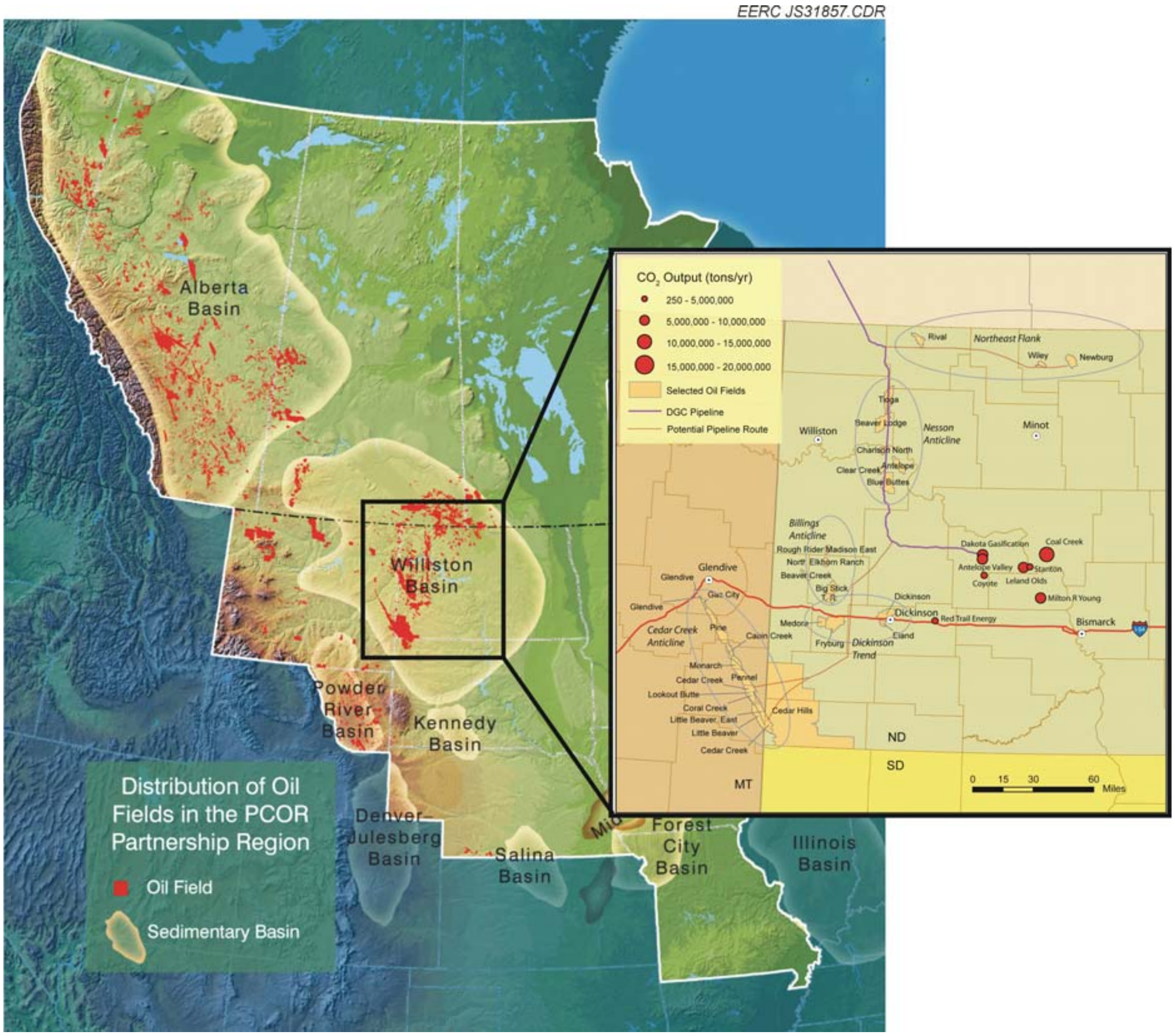

Figure 1. Location of the Williston Basin and oil fields that are being considered as candidate sites for the Phase III Williston Basin CCS Project.

efficacy of large-scale CO_2 sequestration in two locations, including the Williston Basin CCS project. The carbonate oil reservoirs that are being considered in the Williston Basin as targets for large-scale CO_2 flood EOR are similar in many respects to deep carbonate oil reservoirs that are not only found in sedimentary basins of the PCOR Partnership region (Figure 2), but also around the world. It is, therefore, anticipated that the results generated at the Williston Basin site will provide insight and knowledge that can be directly and readily applied throughout the world.

GEOLOGY OF THE WILLISTON BASIN AREA

The Williston Basin is a relatively large, intracratonic basin with a thick sedimentary cover in excess of 16,000 ft. The sedimentary succession in the Williston Basin consists of 50 formally

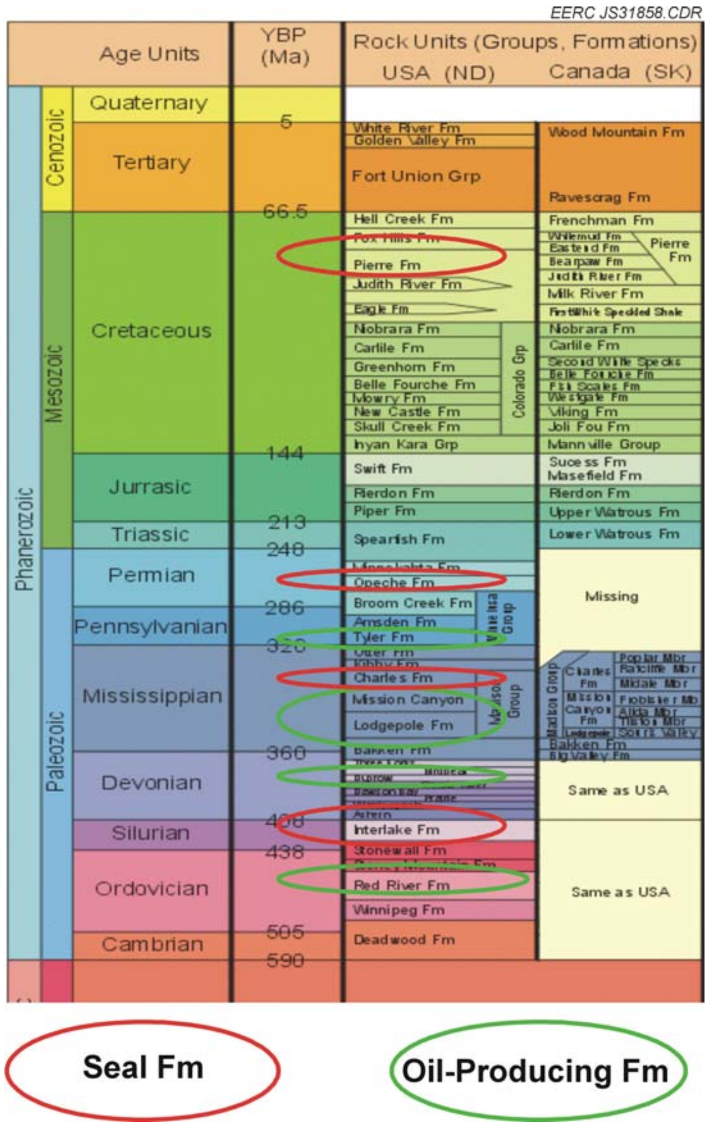

Figure 2. Stratigraphic delineation and nomenclature for the Williston Basin.

named rock formations representing all of the periods of Phanerozoic time, from the Cambrian to the Quaternary. Oil-bearing formations that contain reservoirs that may be suitable for CO_2-based EOR efforts under Phase III (all of which are carbonates) include, in ascending order, the Ordovician Red River Formation, Devonian Duperow Formation, and Mississippian Lodgepole and Mission Canyon Formations. Formations that are considered as likely having sufficiently low permeability to serve as primary sealing formations include, in ascending order, tight carbonates of the Silurian Interlake Formation, salts of the Devonian Prairie Formation,shales of the Devonian–Mississippian Bakken Formation, anhydrites of the Mississippian Charles Formation, and shales of the Permian Opeche Formation, Permian–Triassic Spearfish Formation, and Cretaceous Pierre Formation. The relative stratigraphic position of these potential sink and seal formations and all other rock formations in the Williston Basin are shown in Figure 2. The

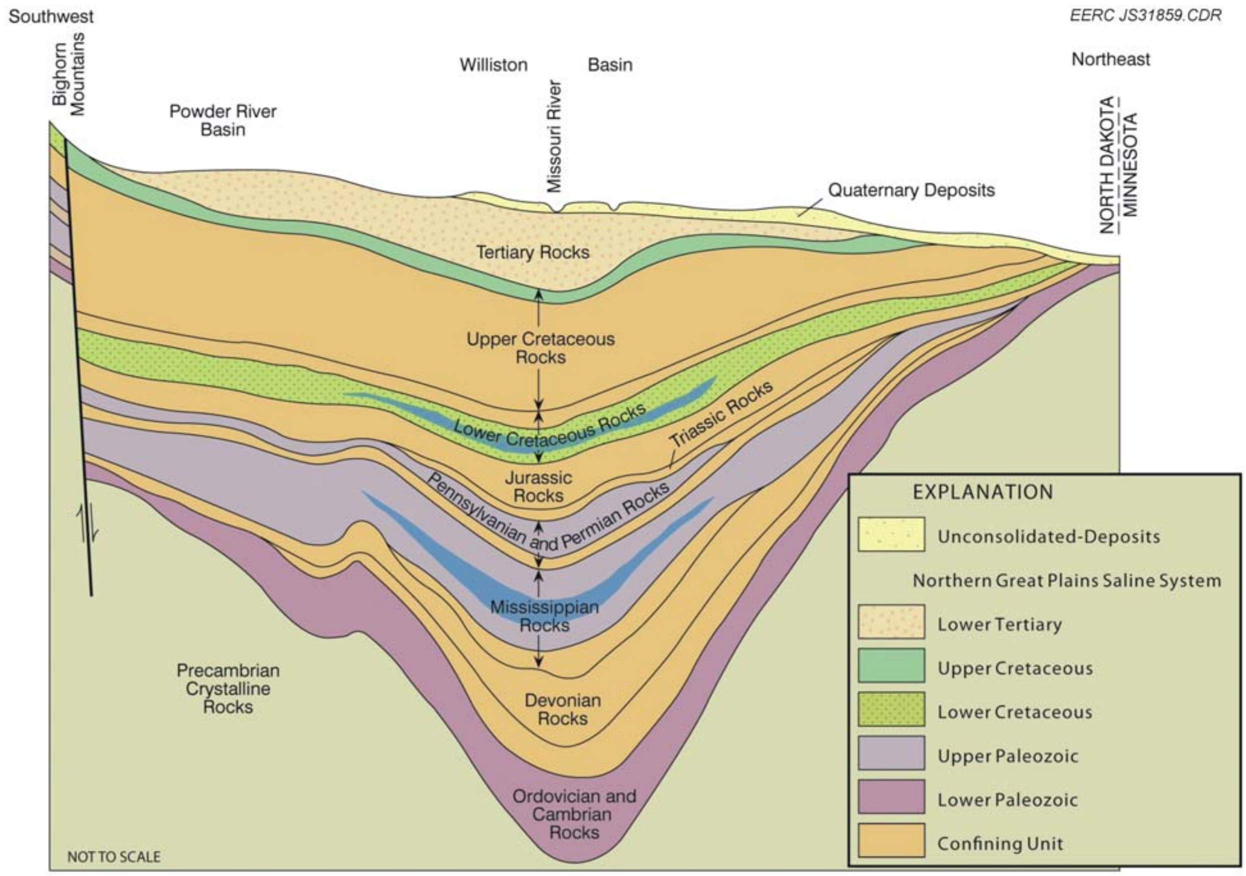

Figure 3. Generalized stratigraphic architecture of the Williston Basin.

Williston Basin is considered by many to be tectonically stable, with a subtle structural character marked by only a few anticlinal structures with low to moderate relief (Figure 3). The stratigraphy of the area is well studied, especially in those intervals that are oil-productive. Many of the potential reservoirs in the basin are vertically stacked (occur above and below each other). Competent traps can be demonstrated locally and, in some cases, regionally. Most of the hydrocarbons produced in the Williston Basin are from carbonate reservoirs that range in age from Ordovician to Mississippian. Although these carbonates represent a potentially significant sink for CO_2 sequestration, porosity distribution within these intervals is not uniform and, where present, is often compartmentalized. Porosity, and permeability to some extent, is controlled by depositional environments. The stratigraphy of these environments is complex and changes rapidly, both vertically and horizontally. Because of reservoir heterogeneity, detailed regional and localized stratigraphic studies will be needed prior to full-scale implementation of CO_2 sequestration. Exploration activities for mineral and energy resources in the area over the last 50 years have yielded a significant amount of information about the geology of the Williston Basin. The carbonate platforms and reefs of several Paleozoic formations in the Williston Basin are known to contain large quantities of hydrocarbons, which suggests that the formations have adequate porosity, permeability, and trapping mechanisms to support the long-term storage of large volumes of CO_2 (Sorensen et al., 2005; Stewart and Bachu, 2000). The geomechanical properties of at least one of these formations will be determined.

CURRENT ESTIMATED CONDITIONS

Because of the complexity and inherent heterogeneity of carbonate rock systems and the fact that a specific location has not yet been chosen to host the injection project, the current conditions of the anticipated target injection formations are not known.

WORK PLAN

It is anticipated that the Williston Basin CCS Project will include the drilling of new wells for either injection or production. Such drilling activities will 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 new well. If core from the new well is not available or the oil field operator determines that new wells are not necessary, then efforts will be made to obtain core samples of the same key formations from other previous drilling activities in the area for use in the geomechanical evaluations. The activities, tasks, and deliverables described herein are derived primarily from the PCOR Phase III continuation application Statement of Project Objectives dated September 5, 2007. 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 MMV operations at a location that is annually injecting over 500,000 tons of CO_2 into a carbonate oil reservoir formation for EOR and long-term sequestration.

The goal of the geomechanical characterization program is to establish the geomechanical properties of the key sink and seal formations 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 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 robust geomechanical modeling.

EXISTING DATA RECONNAISSANCE, ACQUISITION, AND INTEGRATION

A wide variety of previously generated data will be collected during Year 1 of the Williston Basin CCS Project. The North Dakota Department of Mineral Resources Oil and Gas Division (OGD) will provide the PCOR Partnership with most of the 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 potential host site areas, 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 to the geomechanical properties and integrity of the key sink and seal formations.

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

The existing data sets provided by OGD will be integrated into the PCOR Partnership Web-based Decision Support System (DSS). Specifically, a portion of the DSS (designated the "Williston Basin Zone") will be devoted to storing and maintaining all data collected and generated over the course of the Williston Basin CCS project. The Williston Basin zone of the DSS will, at times, contain confidential information and will, therefore, be password-protected. Access to the Williston Basin Zone of the PCOR Partnership DSS will only be granted to Williston Basin CCS project team members and members of the PCOR Partnership that are approved by the EERC (in its capacity as the PCOR Partnership managing entity).

NEW WELL-DRILLING PROGRAM

It is anticipated that the Williston Basin CCS project will include the drilling of one well into the potential target injection formations in the host oil field. If drilled, priority activities will include the collection and analysis of rock core samples and a variety of geophysical logging data. Specific activities that are anticipated to be included in the Williston Basin CCS well-drilling program, and which may have some bearing on the characterization of geomechanical properties, include the following:

- Collection of core and cuttings

  - Cuttings will be collected at 5-m intervals from a depth of 2000 ft from surface to total depth of the well (between 8500 ft and 11,000 ft).

  - Cuttings will include samples from several formations including all of the potential seal and sink formations.

  - A yet-to-be-determined length of core will be collected, with a goal of obtaining significant lengths of core from both the target injection formation and the overlying primary seal formation.

- Core tests will include a variety of permeability and geomechanical parameters, including relative permeability of CO_2 and brine and dynamic and static compressibility, among others.

- The logging suite will include density, neutron, caliper, dipole sonic, and formation microimager, which will provide data on the presence and orientation of fracture systems and local stress regimes.

- Pressure transient analyses

  - Analyses will support injection design and pressure buildup/falloff prediction.

- Initiation and completion of minifrac tests

  - Anticipate at least one minifrac test will be conducted to evaluate the competency of at least one potential sealing formation.

LABORATORY-BASED GEOMECHANICAL INVESTIGATIONS

It is anticipated that core from the well, or from previous drilling activities in the vicinity of the test site, will be available for testing in the summer of 2009. Sets of 1.5-inch-diameter core samples representing the cap rock and reservoir from the Williston Basin CCS study area will be obtained either from the North Dakota Geological Survey core library or from the oil field operator partner and 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. The tests are tailored to find 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:

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

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. If Equation 1 holds or the left part exceeds the right part, then failure occurs.

The Mohr–Coulomb criterion also sets limitations on σ_1 and σ_3. According to the criterion, failure occurs if the following equation holds:

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

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

Other parameters, such as uniaxial tensile strength, will also 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.

Criteria 1 and 2 provide useful estimates in cases where the stress tensor is known. However, 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 reef, 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 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 MMV.

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 Williston Basin CCS Project site have sufficiently high mechanical strength to allow for the safe and effective injection of approximately 1 million tons per 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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