Geomechanical testing and modeling is one of the primary characterization activities employed at the Zama acid gas EOR, CO₂ sequestration, and monitoring project. Program components include laboratory tests, log analysis, field stress testing, and numerical modeling to establish the overall integrity of the system. Initial results from this program indicate that the cap rock has a high mechanical strength, high stiffness, low compressibility, and very low permeability. These results demonstrate that the injection zone and cap rock at the F-Pool pinnacle reef have suitable characteristics for the long-term containment of acid gas.

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1. Introduction

Carbon dioxide capture and storage (CCS) in geological media has been identified as an important mechanism for reducing anthropogenic greenhouse gas (GHG) emissions currently vented to the atmosphere. Several means for geological storage of CO₂ are available, such as in depleted oil and gas reservoirs, in deep saline aquifers, in CO₂-flood enhanced oil recovery (EOR) operations, and in enhanced coalbed methane recovery. Studies in CO₂...
capture, transportation, storage, and monitoring, mitigation and verification (MMV) have been, and continue to be, pursued to allow for the deployment of large demonstrations. Understanding the fate of the injected CO\textsubscript{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\textsubscript{2} geological storage is a safe operation. Second, markets need assurance that credits are properly assigned, traded, and accounted for. Integrated geological and hydrogeological characterization and geochemical sampling and analysis programs are technologies that can document the movement of the injected gases and detect potential leakage from the storage unit.

The Energy & Environmental Research Center (EERC), through the Plains CO\textsubscript{2} Reduction (PCOR) Partnership, one of the U.S. Department of Energy (DOE) National Energy Technology Laboratory’s Regional Carbon Sequestration Partnerships, is working with Apache Canada Ltd. to determine the effect of acid gas (H\textsubscript{2}S and CO\textsubscript{2}) injection for the simultaneous purpose of disposal, sequestration of CO\textsubscript{2}, and EOR. The injection process and subsequent hydrocarbon recovery are being carried out by Apache Canada Ltd., while the EERC and its contractors are conducting MMV activities at the site. The MMV activities have been designed in such a way as to be cost-effective and cause minimal disruption to ongoing oil production activities, yet provide critical data on the behavior and fate of the injected acid gas mixture.

The field validation test, conducted in the Zama oil field of northwestern Alberta, Canada (Figure 1a), is evaluating geological sequestration of CO\textsubscript{2} as part of a gas stream that includes high concentrations of H\textsubscript{2}S (20% to 40%). The results of this project provide insight regarding the impact of H\textsubscript{2}S, in conjunction with CO\textsubscript{2}, on sink integrity (i.e., seal degradation), MMV techniques, and EOR success within a carbonate reservoir. Monitoring activities are focused on the near reservoir environment including cap rock integrity, wellbore leakage, and spillpoint breach. This research project is focused on one pinnacle reef structure approximately 1200 meters tall and 40 acres at the base. As Figure 1b illustrates, there are over 800 such structures that have been identified in this field, five of which are currently accepting acid gas for EOR and the remainder in various stages of primary and secondary oil recovery efforts.
Acid gas injection takes place into the top of a pinnacle reef structure (a process referred to as “top-down” injection) which has been depleted of oil through primary and secondary (water flood) production techniques since the mid-1960’s. Incremental oil is produced from a second well in the reservoir completed near the base of the reservoir. A third well that formerly penetrated the production zone within the pinnacle but was subsequently plugged off and recompleted into a shallower stratigraphic horizon is being used to monitor fluid chemistry and pressure.

The acid gas used in this project is obtained from the Apache Canada Ltd. Zama gas-processing plant and injected into the reservoir at a depth of approximately 1500 meters (4900 feet). The plant currently generates about 360 tonnes/day of acid gas. This amounts to approximately 275 tonnes/day of CO₂ and 85 tonnes/day of H₂S. At the time of this report, approximately 20,000 tonnes of acid gas has been injected. Over the 4-year life of the project, between 30,000 and 60,000 tonnes of acid gas are expected to be injected into the pinnacle. Some recycling of this gas will occur through the EOR process, but it is likely that most of the injected gas will remain in the injection zone resulting in the sequestration of as much as 42,000 tonnes of CO₂ in this single pinnacle.

2. Background

A suite of activities focused on geomechanical characterization has been performed to confirm the mechanical integrity of the reservoir and cap rock system. Figure 2 is a generalized flowchart showing the procedures used to evaluate geomechanical risks in a GHG sequestration project. Historical analytical work was examined, including wireline log data that provided information on dynamic elastic properties and stress regimes and data that allowed for the correlation of static-to-dynamic elastic properties and geomechanical simulation. Hydrogeological evaluations have shown that the reef does not appear to be in communication with adjacent reefs and can be considered a closed system [1]. Thus pressure can experience a significant buildup during the injection period. Previous pressure fluctuations of the reservoir during water flood activities and the irregular shape of the structure (Figure 3) can cause stress concentrations that are a primary focus of evaluation. Geomechanical testing and modeling will help establish the thresholds and integrity of the system when subjected to injection of acid gas at pressures exceeding the initial in situ conditions. New laboratory tests have been conducted, including compression and sonic tests. The compression tests yielded information on strength, static and dynamic elastic properties, compressibility, and stress-dependent permeability. The sonic tests provided data on compressional and shear wave velocities. These data sets, along with data collected in subsequent tests that are ongoing, will ultimately form the basis for developing numerical models that will be used to assess the long-term integrity of the reservoir/cap rock system.

![Figure 2. Geomechanical workflow process.](image-url)
3. Geomechanical properties

Figure 4 shows a log-derived rock strength and elastic properties profile in the Muskeg anhydrite (cap rock) and Keg River dolomite (reservoir) formations from ACL Zama 6-4-116-6W6 between 1440 and 1570 mKB MD. Shear sonic velocity was derived from Vp-Vs relationships calculated from the offset well ACL Amber 8-7-116-6W6. Empirical relationships between static and dynamic Young’s modulus, and unconfined compressive strength (UCS) were defined using the ROCKSBank [2] mechanical properties database and an extensive laboratory testing program conducted for the project.
Figure 5 is a photograph of dolomite and anhydrite core from Apache Zama 6-4-116-6W6. Unsaturated core plugs of these lithologies were tested under triaxial and unconfined conditions to obtain basic rock mechanical and acoustic properties. Figure 6 shows the typical axial and radial strain versus axial stress curves for Muskeg Formation anhydrite.

Figure 7 shows linear Mohr–Coulomb failure envelopes for the Keg River Formation dolomite (the reservoir) and Muskeg Formation dolomite and anhydrite (the cap rock) from core obtained from Apache Zama 6-4-116-6W6. The results are summarized in Table 1. Note the relatively high friction angles (52° and 53°) and peak cohesion values for the anhydrite cap rock.
Uniaxial pore volume compressibility (PVC) tests were conducted on core plugs of vuggy dolomite from the Keg River Formation reservoir, sampled in Apache Zama 6-4-116-6W6. Figure 8 shows the measured relationship between PVC and pore pressure for tests performed with a hydrostatic confining pressure of 31.9 MPa.

4. Preliminary geomechanical simulations

To make a preliminary assessment of the magnitude of in situ stress changes developed in the reservoir and the cap rock as a consequence of initial oil production, subsequent water flooding, and recent acid gas injection the 2-D finite differences-based geomechanical simulation code FLAC2D (Itasca Consulting Group) was used. In situ stresses, formation pressures (from a CMG GEM model) and mechanical properties were input into the model to make first-order deterministic predictions of reservoir and cap rock deformations, induced normal and shear stresses, and to assess the propensity for fault reactivation and movements on natural fractures. Figure 9 shows one realization of the development of shear stresses adjacent to the F-Pool pinnacle reef at a reservoir pressure of 28 MPa. Detailed simulation studies of the pool’s history and the in situ stress changes that have resulted are in progress.
5. Path forward

New core was collected from a well in the vicinity of the F-Pool in March 2007. The new 17-m core includes portions of the Muskeg and Keg River Formations. This core will be used to evaluate the transition zone from cap rock to reservoir rock. Additional core was obtained in late 2008 from an overlying formation in the Zama Field that has been exposed to high concentrations of acid gas in earlier disposal operations. All cores are being evaluated with respect to geomechanical, geochemical, and mineralogical characteristics. Work is also continuing on the development of a more robust coupled geomechanical model for the Keg River reservoir and the Muskeg cap rock, incorporating new procedures for injection- or depletion-induced stress changes. The results of these, and future, analyses will provide a basis for developing predictive models that can be used to evaluate the effects that large-scale acid gas injection can have on reservoir and cap rock.
6. Conclusions to date

Research activities in the Zama project have been conducted to investigate the geomechanical properties and in situ stresses in the Keg River Formation reservoir and the Muskeg Formation cap rock. Geomechanical testing in the laboratory, log analysis, field stress testing, and numerical modeling guide injection pressure thresholds and, hence, ensure the overall integrity of the system. Laboratory tests have been conducted on core samples taken from the Zama Field, including uniaxial and triaxial compressive strength tests, static and dynamic elastic properties, pore volume compressibility, stress-dependent permeability, and compressional and shear wave velocities at varying stress levels. The following represent the current status of key findings with respect to geomechanical testing and analysis for the Zama project:

- Old core from initial wells drilled in the Zama Field in the late 1960s can be used to measure representative rock mechanical and acoustic properties in the laboratory for these relatively stiff reservoir and cap rock strata.

- Correlations between log-derived dynamic and static laboratory elastic and strength properties have been developed for the reservoir and cap rock units of interest in this setting.

- The potential for cap rock leakage due to a geomechanical mechanism appears to be very low at the F-Pool pilot setting, based on data analyzed to date.

Numerical and analytical geomechanical modeling have been used to examine perturbations in the reservoir pressure, and hence the in situ regimes in the reservoir and cap rock, throughout the history of the field’s initial oil production, water flooding, and most recently, acid gas injection. Initial results from this integrated investigative program in the Zama Field indicate that the anhydrite cap rock is generally characterized by high mechanical strength, high stiffness, low compressibility, and very low permeability.

References

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