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Zama Acid Gas EOR, CO_2 Sequestration, and Monitoring Project

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Abstract

Since October 2005, the Zama oil field in northwestern Alberta, Canada, has been the site of acid gas (approximately 80% CO_2 and 20% H_2S) injection for the simultaneous purpose of enhanced oil recovery (EOR), H_2S disposal, and sequestration of CO_2. Beginning in December 2006 and continuing through the present, injection has taken place at a depth of 1494 meters into one of over 800 pinnacle reef structures that have been identified in the Zama Subbasin. To date, over 36,000 metric tons of acid gas has been injected, resulting in incremental oil production over 25,000 barrels. Cost-effective monitoring at EOR sites that utilize H_2S-rich acid gas as the sweep mechanism has been the overall goal of the project. The primary issues that have been addressed include 1) cap rock leakage, 2) long-term prediction of injectate, and 3) generation of data sets that will support the development and monetization of carbon credits. To address these issues, activities have been conducted at multiple scales of investigation in an effort to fully understand the ultimate implications of injection. Geological, geomechanical, geochemical, and engineering work has been used to fully describe the injection zone and adjacent strata in an effort to prove the long-term storage potential of this site. Through these activities, confidence in the ability of the Zama oil field to provide long-term containment of injected gas has been achieved. Results obtained from these activities can be applied not only to additional pinnacles in the Alberta Basin but to similar structures throughout the world.

Keywords: CO_2; Acid Gas EOR; MVA; Geology; Geomechanics

Introduction

The Energy & Environmental Research Center (EERC), through the Plains CO_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_2S and CO_2) injection for the simultaneous purpose of disposal, CO_2 sequestration, and enhanced oil recovery (EOR). The reservoirs in the Zama oil field exist in the form of isolated, porous, and permeable pinnacle reefs (carbonate rocks) sealed by a thick layer of essentially impermeable anhydrite

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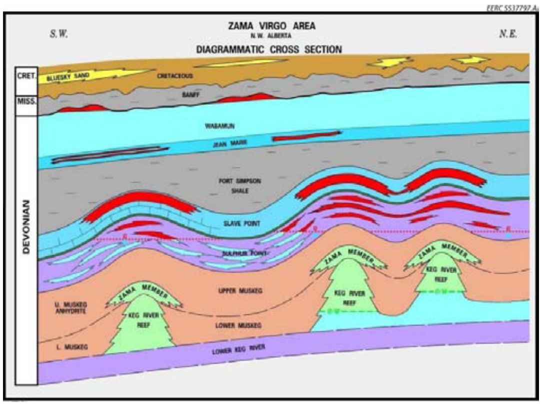
(Figure 1). The capture, transportation, and injection processes and subsequent hydrocarbon recovery operations are being carried out by Apache Canada at its oil field and natural gas-processing plant locations near Zama, Alberta, Canada (Figure 2). The role of the PCOR Partnership was to conduct monitoring, verification, and accounting (MVA) activities at a specific location/reservoir (referred to as the "F Pool") within the Zama oil field. The MVA activities have been designed in such a way as to be cost-effective, cause minimal disruption to ongoing oil production activities, and yet provide critical data on the behavior and fate of the injected acid gas mixture within the reservoir.

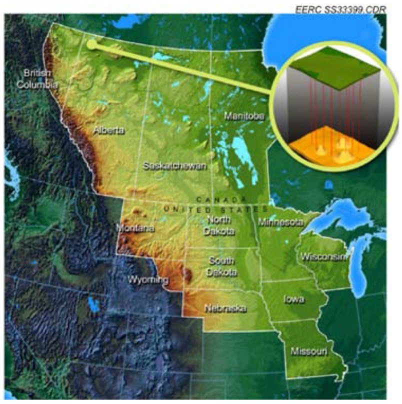
The Zama project was designed with the following goals in mind:

- To demonstrate that the capture and injection of an acid gas stream into properly characterized and carefully selected underground reservoirs is feasible and safe within existing industry and regulatory standards.
- To design, implement, and demonstrate cost-effective MVA strategies for verifying and validating the containment integrity of the target reservoirs.
- To demonstrate that highly concentrated acid gas (in this case, 30% H_2S and 70% CO_2) can be successfully used for EOR operations in a type of geological feature (carbonate pinnacle reefs) that had previously been untested with respect to acid gas-based EOR.

Philosophical Approach

A broad range of technologies and approaches can be and, in some cases, have been applied to CO_2 storage projects of various scales around the world. Early geological storage research and demonstration projects deployed MVA strategies that were developed based on a lack of knowledge about the effectiveness and utility of many of the applied technologies. The absence of knowledge required early projects to gather as much data as possible using a wide variety of techniques. In particular, a desire to "see" the plume of injected CO_2 led to a strong emphasis on the use of geophysical data, especially 3-D and 4-D seismic, to monitor the plume. While the use of geophysically based approaches and techniques in early projects yielded valuable results that are essential to the development of geologic storage as a CO_2 mitigation strategy, their high costs of deployment and often limited ability to identify CO_2 in many geologic settings may render them as being the exception rather than the rule when it comes to developing practical MVA plans for future projects. If the implementation of carbon capture and sequestration (CCS) is to occur on a





Figures 1 and 2 Figure 1 illustrates a generalized cross section through the Zama area demonstrating the isolated nature of Keg River Formation pinnacle reefs and the encapsulating anhydrite of the Muskeg Formation. Figure 2 shows the project location within the PCOR Partnership region.

large enough scale to mitigate global climate change, then economics must be secondary only to health and safety considerations at the earliest stages of project development. At the same time, a detailed understanding and effective demonstration of the technical feasibility with respect to injectivity, capacity, containment, and overall safety are essential for all stakeholders to buy into the concept of large-scale CO_2 and/or acid gas injection. This is the context within which a philosophical approach was developed, which was then applied to the PCOR Partnership Phase II Program.

It is expected that, in many cases, EOR projects and depleted oil and gas pools will provide the most favorable locations for long-term CO_2 storage from both a technical and economic standpoint. From a technical perspective, such sites benefit from a relative wealth of previously generated, readily available subsurface characterization and reservoir production and injection data. These data provide critical, invaluable insight regarding the long-term prospects for technically feasible and safe injection and storage of acid gas. From an economic perspective, hydrocarbon reservoirs (and especially those that are suitable for EOR projects) are attractive because the use of existing infrastructure can lower the start-up costs of a project, while the production of incremental oil can be used to offset the costs of capital, operations, and maintenance and, ultimately, bring profitability to the project. The use of established hydrocarbon reservoirs also benefits from the fact that a regulatory framework already exists for permitting many, if not all, of the surface and subsurface operations that will be necessary to conduct a project.

The philosophical approach of the PCOR Partnership toward the design, implementation, and operation of the MVA plan and associated project activities was to 1) maximize the use of previously generated data on the geological, geochemical, and geomechanical characteristics of the formation into which acid gas was to be injected (target injection zone) and the overlying low-permeability rock formations that would serve as seals, and 2) minimize, as much as possible, the need to obtain data beyond that which are already collected by the operator as part of the "normal" or "standard" operation of an EOR or acid gas disposal project. For those elements of the MVA plan that required the use of new or nonstandard testing or technologies in the field, those elements would be designed in close consultation with the field managers and operators to ensure that disruption of normal oil field operations was minimized.

The application of these fundamental guiding principles to the planning and operation of the Zama project ensured that the goal of demonstrating the economic feasibility of acid gas injection for simultaneous EOR and CO_2 storage under "real-world" technical and economic constraints could be achieved. That being said, the PCOR Partnership and Apache Canada recognized the value of developing previously unavailable fundamental data sets that could provide new understanding of CCS and guide the direction of future CCS research. With that in mind, the PCOR Partnership sought and, when appropriate, acted on opportunities to cost-effectively conduct additional activities that were of a more research-oriented nature and which would not typically be part of future nonresearch EOR and/or CCS projects.

Technical Approach

For the purpose of discussion, the technical aspects of the PCOR Partnership Phase II–Apache Canada project at Zama generally can be thought of as falling into two categories: 1) the MVA program and 2) the injection program. These categories are necessarily dependent on each other, with some activities and data sets being common between the two categories. However, for the sake of effective discussion, they are presented in relatively independent sections, with categorization based largely on what was deemed to be the primary purpose of each activity.

The purpose of the MVA program is to 1) provide a set of baseline conditions upon which the effects of the project can be compared to data gathered during and after injection operations, 2) generate data sets that demonstrate the security of the injection program from the perspectives of containment and safety, and 3) establish a technical framework for the creation and ultimate monetization of carbon credits associated with reduction of emissions and the geologic storage of CO_2 at Zama. MVA program activities that resulted in the determination of baseline conditions include geologic and hydrogeologic characterization at various scales, characterization of the F pool reservoir, determination of geomechanical and geochemical properties of key rocks in the reservoir/seal system, and evaluation of wellbore integrity issues. Field-based elements of the MVA program include the introduction of a tracer and data collection (i.e., formation fluid sampling and analysis, reservoir dynamics monitoring) from the injection, production, and monitoring wells. Other key elements of the MVA program include documentation of the permitting process and regulatory framework for the project, determination of a material balance based on the collected field data, and a modeling-based study of historical and new reservoir pressure data in an effort to maximize the use of pressure data as a means of early identification of leakage. Generally speaking, monitoring activities are focused on the near-reservoir environment, including monitoring for leakage through cap rock, wellbore leakage, and spillpoint breach (Figure 3).

The purpose of the injection program is to 1) ensure the cost-effective injection of acid gas from the Zama gas-processing plant into the Zama F Pool reservoir, 2) facilitate the production of incremental oil from the F Pool reservoir, and 3) support the documentation of effective CO_2 storage in the F Pool. Key aspects of the injection program include the capture and infrastructure elements of the project, well preparation and maintenance activities, and acid gas injection and EOR operations.

Key Observations, Challenges, and Lessons Learned

The PCOR Partnership's Phase II activities at Zama combined a wealth of historical information with newly generated laboratory- and field-based data to develop a broad range of previously unavailable insights regarding the injection of acid gas for EOR and CCS. These insights can provide stakeholders and planners of similar future projects with the ability to make informed decisions for a variety of design elements. Project-critical technical areas for which information was compiled include baseline geologic and hydrogeologic characterization, wellbore integrity issues, determination and implications of geomechanical properties of reservoir and seal rocks, expectations for geochemical interactions, prediction of near- and long-term effects and fate of the injected gases, and design and operation of wells and surface infrastructure in the presence of high concentrations of acid gas. Some of the key observations, challenges, and lessons learned over the course of the Zama acid gas injection project are briefly summarized below.

Acid Gas Injection and Oil Production

The injection of acid gas into the Zama Keg River F Pool pinnacle reef was initiated in December 2006. Injection continued well into 2009, with some interruption for well maintenance; Apache Canada plans call for continued injection beyond 2010. To date, a cumulative total of over 2.3 million cubic meters (approximately 36,000 metric tons) of gas has been injected, with an average composition of 80% CO_2 and 20% H_2S. This equates to approximately 18,000 metric tons of CO_2 stored throughout the operational period. Injection rates throughout this reporting period have remained relatively stable at approximately

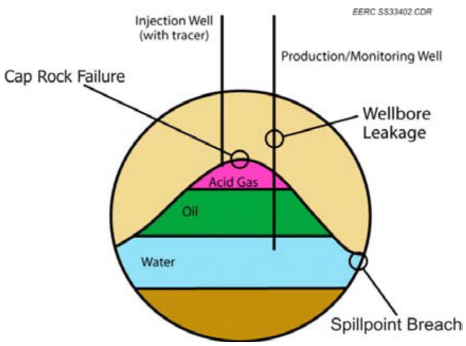


Figure 3 Monitoring activities at Zama focused on assessing the potential for leakage out of the reservoir through the cap rock, wellbores, and spillpoint at the base of the structure.

28316.85 cubic meters a day but have generally increased over the past year to meet voidage replacement demands. Oil is currently being produced at an average rate of 100 barrels per day. As of August 30, 2009, 25,000 barrels of oil have been produced from this pinnacle.

Suitability of Pinnacle Reefs for Acid Gas Injection and Long-Term CCS

Based on the available data, the geological studies concluded that the injection of acid gas into the pinnacle reefs of the Zama Keg River Formation is a safe operation [1]. The acid gas is confined to the injection horizon by the reef structures that originally trapped the oil and gas. There is minimal potential for acid gas leakage through faults and fractures in the Zama area or for acid gas migration to shallower strata, potable groundwater, or to the surface as a result of flow through naturally occurring permeability streaks or flow paths.

The strength of the reservoir and cap rock formations, as determined by the geomechanical and geochemical evaluations, combined with the closed architecture of the pinnacle structure and the very conservative maximum operating pressures leave little possibility of lateral migration outside of the reef structures. Further, the results of the regional hydrogeological study indicate that any potential dispersion beyond the individual pinnacle spillpoints into the regional aquifer would still result in storage occurring before the plume had traveled a significant distance, e.g., the maximum velocity of the formation water is sufficiently slow that it would take as much as 800,000 years for a fluid molecule to reach a Keg River Formation outcrop.

When combined with data from laboratory pore entry mercury injection pressure tests and mechanical stress testing on similar area cores, as well as log analyses and drilling reports, there is strong evidence that the thick (60–90 m) Muskeg Formation dolomite/anhydrite sequences provide a competent, dense, and essentially impermeable cap rock above the Keg River pinnacles [1]. These data suggest that the F Pool pinnacle integrity far exceeds the current Energy Resources Conservation Board of Alberta (ERCB) EOR pressure limit [2], and it could be proposed that following the completion of the EOR recovery, additional CO_2 and/or acid gas volumes could be stored within this pinnacle by increasing the allowable storage pressure beyond the original reservoir pressure.

Over 800 pinnacle reefs are currently known in the Zama subbasin of the Western Canadian Sedimentary Basin. Hundreds of similar pinnacle reefs occur in the Williston Basin, Michigan Basin, and Illinois Basin, just to name a few. The geologic and hydrogeologic studies conducted at Zama provide supporting documentation that pinnacle reefs can be suitable and even excellent sites for CCS.

Relative Mobility and Fate of CO_2 and H_2S Within Carbonate Reservoirs

One set of questions that were identified early in the Zama project were whether or not the primary constituents of the acid gas stream would undergo separation within the reservoir, and if it did occur, what the magnitude, timing, and significance of that separation would be. The results of geochemical modeling conducted that used the geochemical and mineralogical properties of the F Pool reservoir indicated that the leading edge of the acid gas plume will become enriched in CO_2 [3]. This observation was in agreement with the results of field- and laboratory-based analytical activities and other modeling efforts. The enrichment is due, at least in part, to the preferential absorption of H_2S into the aqueous phase. However, in the presence of reactive iron-bearing minerals, other processes can lead to the separation of the two gases. As the acid gas plume reacts with the carbonate minerals, significant amounts of iron and bicarbonate are added to the water. This iron rapidly precipitates as an iron sulfide when H_2S is present in the gas phase. The iron sulfide precipitation produces a significant amount of acid; this acid drives much of the bicarbonate out of aqueous solution, leading to further CO_2 enrichment in the gas plume.

Additional transport studies suggest that containment of the acid gas in a geologic reservoir may be affected by the capillary properties of the acid gas–brine solution in relation to the capillary pore entry pressure of the brine-saturated cap rock system [3]. In particular, the studies suggest that the maximum reservoir pressure limitation to avoid acid gas leakage through, or imbibition into, the cap rock may be lower than current pressure limits derived from mechanical stress testing. The designated maximum operating reservoir pressure will be pool-specific. If a lower maximum reservoir pressure limit is necessary, the estimates for storage capacity in each reservoir will require review. The impact on the gas miscibility with the reservoir oil and the EOR project will also need to be reviewed.

The results of the acid gas mobility and fate investigations conducted as part of the Zama project may be directly applicable not only to the hundreds of similar pinnacles in the Zama subbasin but to acid gas injection projects in carbonate rock formations in general.

Effects of Acid Gas on Wellbores and Surface Infrastructure

The selection of corrosion-resistant materials for well completions and surface infrastructure is critical to the long-term operation and maintenance of an acid gas EOR and/or CCS project. Because of the higher costs of such materials, the judicious application of corrosion-resistant materials in the design of wells and surface facilities is required to maintain the proper balance of performance versus cost. For instance, as a result of the significant incremental costs for corrosion-resistant alloy (CRA) pipe, most CO_2 and acid gas applications have effectively used low-alloy carbon steel protected by coatings or linings for casing and tubing applications. In some circumstances, it may also be appropriate to utilize one or two joints of CRA casing within critical wellbore sections rather than throughout the entire length of the well. Smaller equipment items such as packers, flow control devices, and subsurface safety valves are also often constructed of nickel-based alloys, as it is more difficult to protect all of the wetted and working surfaces of these items with coatings. This approach has been applied successfully to the design of acid gas injection and sour gas production wells at Zama and, in most cases, can be broadly applied to similar injection schemes wherever they may be planned.

The use of corrosion-resistant cements is also a critical component to maintaining wellbore integrity. In general, recent literature suggests that properly designed portland-based oil well cements are very CO_2-resistant. In fact, the results of experimental work presented by Duguid [4] conclude that a properly cemented well with good zonal isolation will be safe for 30,000 to 700,000 years. The literature also consistently shows that while CO_2 and brine mixtures do change the texture and mineralogy of portland cements used in oil wells, those changes do not significantly reduce the hydraulic seal afforded by the cement sheath.

A review of the integrity of the casing cement and completion of the acid gas EOR/CCS wells in the F Pool indicated that the integrity of the current wells is good. With respect to the infrastructure at Zama, some site-specific challenges were encountered, most notably the plugging of flowlines with asphaltines and waxes, particularly during the winter months. These problems were successfully addressed by Apache Canada through the combined use of heated and/or insulated flowlines and the introduction of chemical additives to prevent the coagulation of those materials. It is important to note that none of the operational challenges at Zama is new to the oil and gas industry, and given time and thoughtful consideration, all of them are manageable and should not threaten the commercial use of acid gas injection for EOR or as a viable CCS strategy.

The Use of Pressure Data and Tracers to Detect Leakage

One of the goals of the Zama project was to minimize any disruption to normal commercial oil field operations. One way to achieve this goal was to look for ways to maximize the use of data sets that are routinely gathered over the course of oil field operations. Pressure data, both from the preinjection history of the F Pool and from the injection phase of the project, were identified as one possible way of identifying the leakage of acid gas from the pinnacle reef into an overlying formation [1]. Another technique that would cause minimal disruption to normal operations was to do a one-time injection of a unique tracer compound into the acid gas stream early on during the injection phase and then monitor for that tracer in the various production and monitoring wells as part of periodic sampling and analysis events. In the case of the Zama F Pool, an existing gas production well that was completed into the overlying Slave Point Formation was selected to serve as a monitoring well for both the pressure measurements and tracer analyses (Figure 4).

With respect to the tracer monitoring, a gas-soluble chemical tracer compound (5.5 kg of Core Labs IGT-1100) was injected into the Keg River F Pool in February 2008. The collection and analysis of fluid samples from the Slave Point FFF Pool for the tracer were conducted on a 6-month schedule. No tracer has been detected in any of the gas samples to date.

Historical and current pressure data were gathered for both the Keg River F Pool and the overlying Slave Point FFF Pool. During the Zama injection project, initial pressure testing was performed on the Slave Point FFF Pool in April 2008. A further pressure survey and gas-sampling operation were conducted on December 20, 2008. The historical data combined with the new data allowed for a comparison of the Keg River F Pool and Slave Point FFF pressure histories and indicate a small 200-kPa increase in pressure in the last two Slave Point FFF Pool measurements [1]. At this point, it cannot be determined if this is a result of two different gauge readings, water influx, or an increase of pressure because of seepage. More pressure data are required before the source of any pressure change can be attributed to any of these or any other causes.

Generally speaking, the results of the tracer and pressure-monitoring activities at Zama indicate that both techniques hold considerable promise for application as useful, noninvasive, cost-effective elements of an MVA plan.

Recommendations/Conclusions

Currently, the process of capturing and compressing CO_2 from many stationary sources is both costly and energy-intensive. For this reason, capturing CO_2 from readily attainable, less pure streams of CO_2 from other large point sources are good initial targets for CCS. While the quantity and volume of these impure streams may not be as great as those generated by other sources, i.e., electricity generation from coal, they are significant and contribute to the total CO_2 that is currently emitted to the atmosphere. In the PCOR Partnership region, gas-processing plants, such as the one utilized at Zama and common to oil- and gas-producing regions throughout North America, are emerging as primary targets for CCS demonstrations.

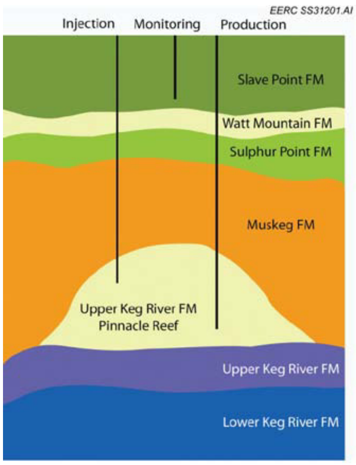


Figure 4 Illustration showing configuration of wellbores in the F Pool pinnacle. Samples to be analyzed for the injected tracer were taken from the Slave Point Formation monitoring well.

As the United States and Canada seek to reduce greenhouse gas emissions, the use of natural gas is expected to increase because of its relative abundance, its lower CO_2/Btu footprint compared to coal, and the likelihood of using it as a primary feedstock for hydrogen production. As demand for natural gas increases, it is likely that less pure reservoirs will be exploited to keep up with demand. This production will include sour gas fields and will ultimately drive demand for new gas-processing plants, leading to an increase in CO_2 streams that include high concentrations of H_2S. These streams will have to be dealt with in some fashion—the most likely being acid gas injection. This process has proven very effective at the Zama site, as evidenced by the success of the EOR project and the associated monitoring program that has proven the field can be utilized for both EOR and CO_2 storage. However, because of the site-specific nature of CO_2 storage projects and differences in lithology, pore fluids, and concentrations of injectate, the need exists to evaluate the injection of acid gas from a more holistic viewpoint.

Key findings from the project indicate that the Zama site is ideal to continue research activities for the following reasons: 1) an excellent partnership with the field operator, Apache Canada Ltd., exists; 2) the unique geologic setting with respect to the isolated nature and geometry of pinnacle reef structures simplifies containment of injected gas; 3) injection of acid gas is ongoing and will continue to remain active as an EOR scheme; and 4) the lithology is commonly found throughout much of the central interior of North America.

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