FACT SHEET FOR PARTNERSHIP FIELD VALIDATION TEST

Partnership Name	Plains CO_2 Reduction (PCOR) Partnership – Phase II	
Contacts:	Name	Organization / E-Mail
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Principal Investigator	Edward Steadman	
Field Test Information: Field Test Name	Zama Field Validation Test	
Test Location	Zama City, Alberta, Canada	
Amount and Source of CO_2	Tons: 20–90 tons/day (approximately 40,000 tons to date)	Source: Zama Gas-Processing Plant
Field Test Partners (Primary Sponsors)	Apache Canada Ltd.	
	Alberta Energy and Utilities Board, Natural Resources Canada	

Summary of Field Test Site and Operations:

The Zama Oil Field

A pinnacle reef structure has been used to demonstrate the efficacy of simultaneous CO_2/H_2S storage and enhanced oil recovery. The Zama oil field in northwestern Alberta (Figure 1) covers an area of about 300,000 acres (1200 km^2) in the Middle Devonian Zama subbasin (Figure 2). The sedimentary succession in the Zama subbasin consists, in ascending order from the Precambrian crystalline basement to the surface, of Middle and Upper Devonian carbonates, evaporites and shales, Mississippian carbonates, and Lower Cretaceous shales overlain by Quaternary glacial drift unconsolidated sediments (Figures 3 and 4).

Oil production is primarily from reservoirs in pinnacle reefs of the Middle Devonian Keg River Formation (Figure 3). These reef buildups were formed in a lagoon partially surrounded by carbonate banks and fronted by the Presqu'ile barrier to the west (Figure 2). To date, over 800 pinnacles have been discovered in the Zama subbasin. The pinnacles, on average, are about 40 acres (0.16 km^2) in size at the base and about 400 ft (120 m) high. They typically consist of dolomite of variable porosity and permeability (average 10% and 100 to 1000 mD, respectively) and are overlain by anhydrite of the Muskeg Formation. While some Keg River pinnacle reefs have grown directly on the underlying low-permeability Lower Keg River carbonate platform (Figure 3), resulting in hydraulic isolation of the individual pinnacle reservoirs, others rest on higher-permeability Keg River bank facies which hydraulically connects several pinnacles, resulting in pressure support from an active water drive.

Reservoir Characterization

The F Pool was discovered in 1967 and brought on production in February of that year. A pressure/volume/temperature (PVT) sample was taken in October of 1967 by the Hudson's Bay Oil and Gas Company Limited and analyzed by Core Laboratories in November of 1967 (Apache Canada Ltd., 2003). The original reservoir pressure was recorded as 2095 psig (14,447 kPa) at datum depth of approximately 5000 ft (1500 m) mean sea level. By November of 1968, special core analysis was conducted on core samples taken during drilling of the 11–25 well (Apache Canada Ltd., 2003). Routine core analysis was performed on the 8-13-116-6W6 discovery well. Cumulative production has been approximately 1.1 million barrels (stb) oil (176,100 m^3), 533 million ft^3 gas (15 million m^3), and 500,000 stb water (70,000 m^3) since inception. As a secondary recovery effort, a brief water injection period was undertaken where approximately 2.3 million stb (366 thousand m^3) was injected into the pinnacle.

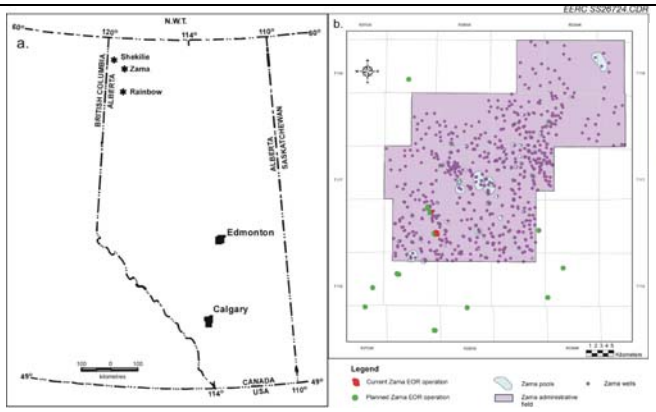


Figure 1. Location of the acid gas enhanced oil recovery (EOR) project at Zama: a) Keg River hydrocarbon fields in northern Alberta (Apache Canada Ltd., 2003) and b) the Apache Canada Ltd. Zama–Keg River acid gas EOR sites in the Zama oil field. Well locations shown are those where the Keg River Formation was penetrated.

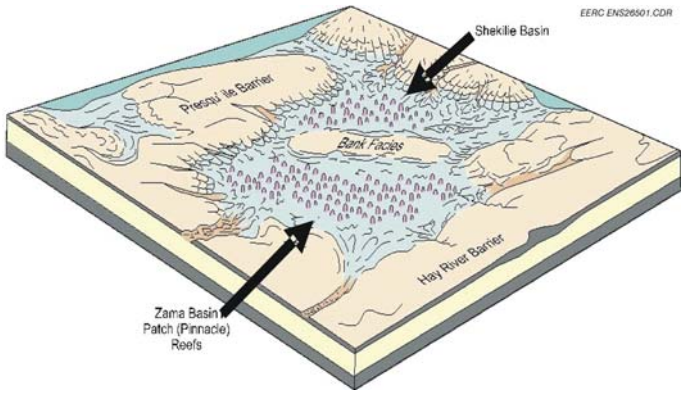


Figure 2. Schematic block diagram showing the Zama and Shekilie subbasins in northern Alberta.

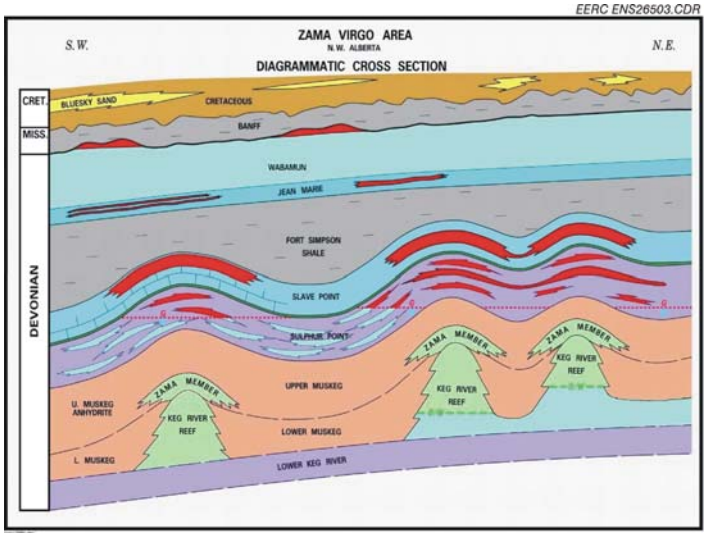


Figure 3. Schematic cross section illustrating the sedimentary succession in northwestern Alberta. Also shown are oil and gas occurrences.

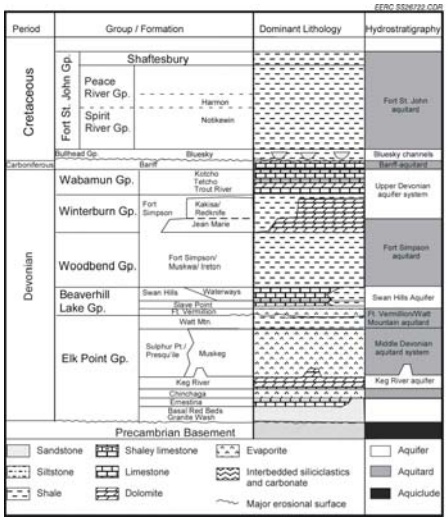


Figure 4. Stratigraphic and hydrostratigraphic delineation and nomenclature as well as general lithology for the northern part of the Alberta Basin.

Research Objectives:

Work Plan

The overall purpose of these activities, from the perspective of the PCOR Partnership, was to create a Regional Technology Implementation Plan (RTIP) best practices manual that outlines a set of guidelines for monitoring, verification, and accounting (MVA) operations at an oil production site that is using acid

gas as a tertiary recovery mechanism for the purposes of EOR and CO_2 storage. One important factor is the effect of H_2S concentrations on EOR, CO_2 storage capacity, and MVA techniques. Research activities related to acid gas injection were conducted at the Zama F Pool in the Zama oil field, Alberta. The goal of the PCOR Partnership's activities at the Zama site was to develop and implement an MVA strategy that establishes the integrity of the Zama pinnacle reefs for CO_2-rich acid gas storage. This was accomplished by carrying out assessments of the baseline geology; rock mineralogy and composition of formation water; hydrogeological system; mechanical rock properties and stress regime; geochemical interactions between formation and injected fluids and reservoir rock and cap rock; and wellbore integrity and leakage potential at the reservoir, local, and regional/subbasin scales.

Summary of Modeling and MVA Efforts:

Modeling

The Zama Keg River F Pool simulation study was conducted by the University of Regina in 2005 with the aim of investigating several injection/production strategies using an available nearby CO_2 gas source. An 8-component Peng–Robison Equation of State was tuned based on PVT lab data and used to simulate the reservoir fluid properties in an effort to better predict CO_2–oil-phase behavior in the pinnacle. Injecting from the top of the formation and producing from the bottom, using the existing vertical wells, gave higher oil recovery and needed less injection pressure. Prediction scenarios for drilling a new well on the other side of the pinnacle gave the highest recovery and improved the sweep efficiency as compared to the case of reentering the existing wells horizontally. In general, most of the predictive scenarios indicated that about 2 months of continuous CO_2 injection was necessary to reach the minimum miscibility pressure and initiate production.

In addition to the petrophysical modeling activities that were conducted to predict reservoir performance, geomechanical and geochemical models were developed for the site. A geomechanical model was created based on the unique geometry of the pinnacle and the contrasting anhydrite and dolomite lithologies. This model was used to predict the ultimate mechanical integrity of this system and the expected response to acid gas injection. Geochemical modeling has been conducted to determine the ultimate fate of injected gas. Rates of mineralization were evaluated with respect to a multiphase system and were used to predict the long-term mobility of CO_2 in the subsurface.

As a means of predicting leakage from the reservoir, an evaluation of historical and current reservoir pressure has been performed. Reservoir pressures were modeled in the Keg River reservoir and overlying Slave Point reservoir to quantify the flux over time and correlate it to injection and production profiles. If wellbore leakage were to occur, an increase in pressure in a porous reservoir should be detectable. This study will result in a greater understanding of wellbore leakage scenarios and will result in recommendations with respect to the pressure difference needed to determine that leakage is occurring.

MVA Efforts

The techniques listed below have been employed over the course of the 4-year project to monitor the effects of acid gas injection at the Zama Field demonstration site. The preinjection state of each of these parameters was determined either by currently available data or field activities to acquire new data.

Measurement Technique	Measurement Parameters	Application
Introduced and Natural Tracers	Travel time Partitioning of CO_2 into brine or oil	Tracing movement of CO_2 in the storage formation Quantifying solubility trapping Tracing leakage

Measurement Technique	Measurement Parameters	Application
Fluid Composition	CO_2, HCO_3, CO_3^{2-} Major ions Trace elements Salinity Hydrocarbon composition	Quantifying solubility and mineral trapping Quantifying CO_2–water–oil–rock interactions Detecting leakage
Subsurface Pressure	Formation pressure Annulus pressure Groundwater aquifer pressure	Control of formation pressure below fracture gradient Wellbore and injection tubing condition Leakage out of the storage formation
Well Logs	Brine salinity Sonic velocity CO_2 saturation	Tracking CO_2 movement in and above storage formation Tracking migration of brine into shallow aquifers Calibrating seismic velocities for 3-D seismic surveys

Accomplishments to Date:

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, and Apache Canada plans call for continued injection beyond 2010. To date, a cumulative total of over 800 million cubic feet (approximately 40,000 tons) of gas has been injected, with an average composition of 80% CO_2 and 20% hydrogen sulfide (H_2S). This equates to approximately 20,000 tons of CO_2 stored throughout the operational period. Injection rates throughout this reporting period have remained relatively stable at approximately 1 million cubic feet per 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 (Figure 5). As of August 30, 2009, 25,000 barrels of oil have been produced from this pinnacle. The RTIP developed by this project was finalized in September 2009. Opportunities for further MVA activities and research exist at this location that is actively injecting acid gas.

Summarize Target Sink Storage Opportunities and Benefits to the Region:

The PCOR Partnership collaborated with Apache Canada Ltd. to determine the effect of acid gas injection for the purpose of simultaneous acid gas disposal, sequestration of CO_2, and EOR. Apache Canada Ltd. is carrying out the injection process and subsequent hydrocarbon recovery, while the Energy & Environmental Research Center was focused on conducting CO_2 MVA activities at the site. This was a unique opportunity to develop a set of MVA protocols for CO_2 sequestration for a commercial-scale hydrocarbon recovery project. Further opportunities to expand said MVA activities exist at this location.

The validation test conducted in the Zama Field of Alberta evaluated the potential for geological sequestration of CO_2 as part of a gas stream that also includes high concentrations of H_2S. The results of the Zama activities provide key insights regarding the impact of high concentrations of H_2S (20% to 40%) on sink integrity (i.e., seal degradation), MV, and EOR success within a carbonate reservoir. The acid gas is sourced at the Zama gas-processing plant and is being injected into a pinnacle reef, the F Pool, at a depth of approximately 4900 feet (1500 meters).

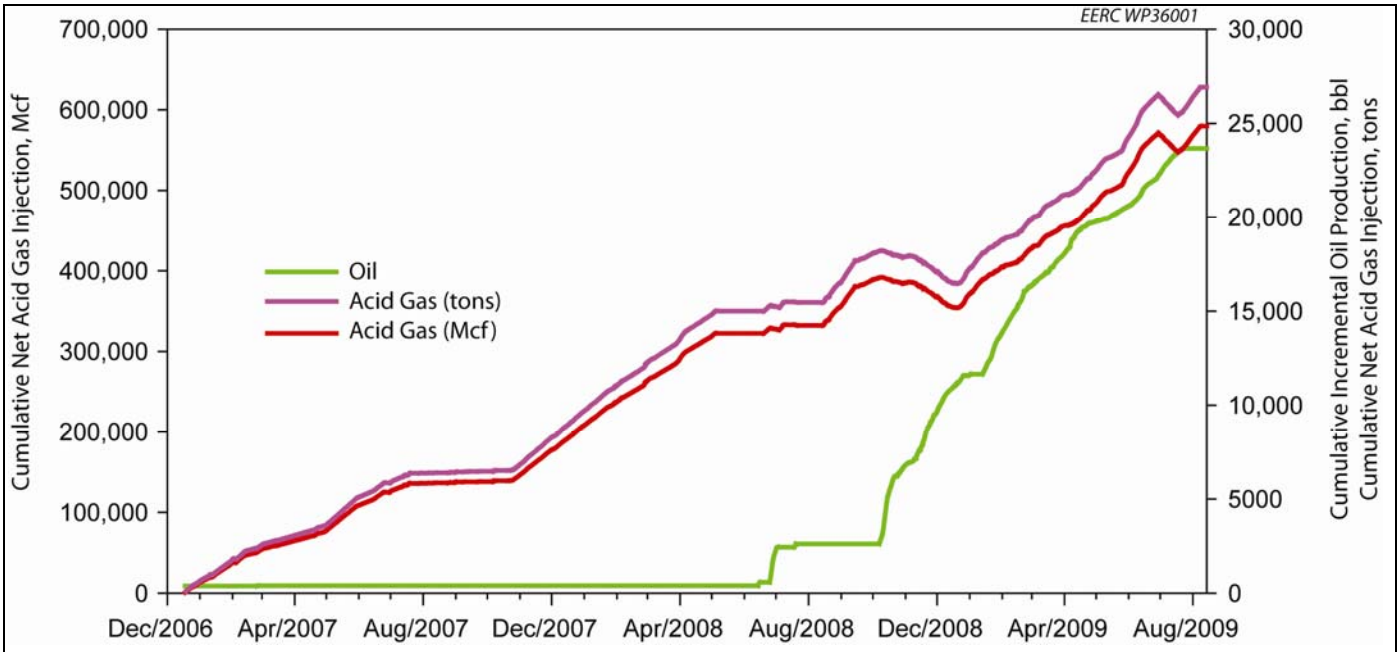


Figure 5. Zama F Pool acid gas injection profile.

The field-wide activities at Zama address two critical environmental issues. First is the reduction of anthropogenic CO_2. Apache Canada plans to continue injecting up to 36,500 metric tons of CO_2 annually. Second, the Zama Acid Gas Miscible Flood Project is injecting the entire acid gas stream into nearby Keg River Formation pinnacles. This will effectively use all of the acid gas handled at Zama as a miscible fluid and has enabled the shutdown of the Claus unit, eliminating the accumulation of elemental sulfur. With respect to EOR, it is anticipated that the acid gas miscible flood will ultimately yield between 180,000 and 276,000 barrels of incremental oil recovery each year.

Cost:

Total Field Project Cost: $7,613,203

U.S. Department of Energy (DOE) Share: $1,375,014 18%

Non-DOE Share: $6,238,189 82%

Field Project Key Dates: See Gantt Chart below.

Baseline Completed: December 1, 2006

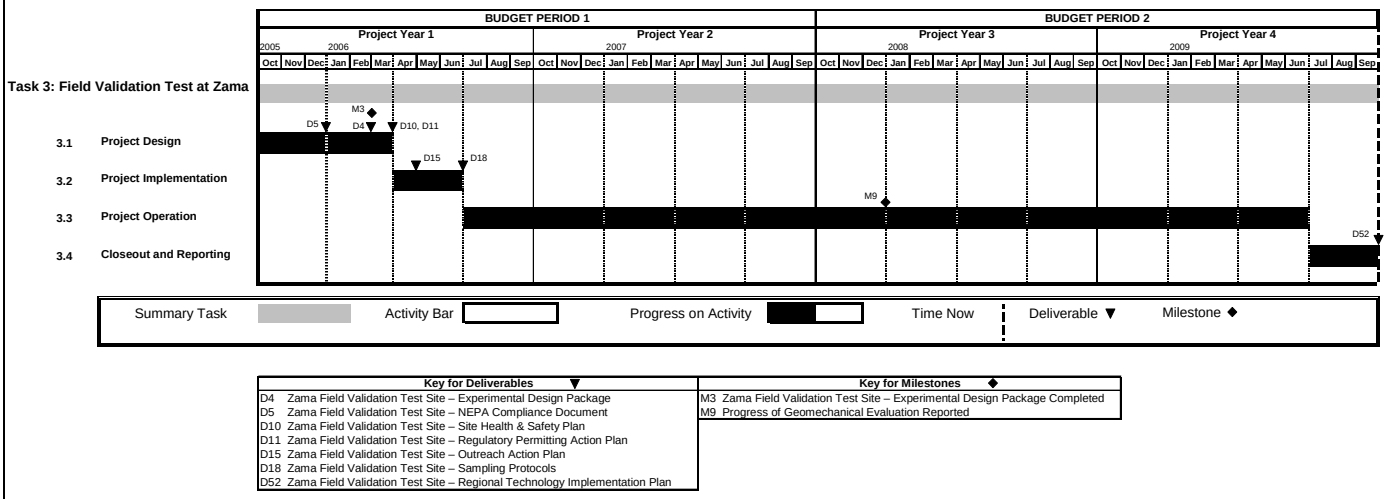
Drilling Operations Begin: Existing wells that have been recompleted are being utilized for injection while a new production well was completed in 2005.

Injection Operations Begin: December 15, 2006

MVA Events: The monitoring well above the injection zone has been sampled and shows no evidence of increase in pressure and acid gas concentrations. This is a positive indication of no leakage.

Field Test Schedule and Milestones (Gantt Chart):

- Experimental Design Package completed February 2006.
- National Environmental Policy Act compliance document completed December 2005.
- Site Health and Safety Plan completed March 2006.
- Regulatory Permitting Action Plan completed March 2006.
- Outreach Action Plan completed April 2006.
- Sampling Protocols completed June 2006.
- Regional Technology Implementation Plan completed September 2009.



Key for Deliverables ▼	
D4	Zama Field Validation Test Site – Experimental Design Package
D5	Zama Field Validation Test Site – NEPA Compliance Document
D10	Zama Field Validation Test Site – Site Health & Safety Plan
D11	Zama Field Validation Test Site – Regulatory Permitting Action Plan
D15	Zama Field Validation Test Site – Outreach Action Plan
D18	Zama Field Validation Test Site – Sampling Protocols
D52	Zama Field Validation Test Site – Regional Technology Implementation Plan

Key for Milestones ◆	
M3	Zama Field Validation Test Site – Experimental Design Package Completed
M9	Progress of Geomechanical Evaluation Reported

Additional Information:

The following reports have been completed through the project since inception:

Acid Gas–Brine Static Partitioning Study
A Study of the Reservoir Condition Drainage and Imbibition Permeability
Displacement Characteristics of Supercritical CO_2 in the Zama Area, Sulfur Point Formation
Experimental Study of CO_2 and H_2S Partitioning in a Brine-Saturated Porous Medium
Evaluation of Zama Field Wellbore Integrity, Part I
Evaluation of Zama Field Wellbore Integrity, Part II (Evaluation of Leakage Potential by Well)
Regional-Scale Geology and Hydrogeology of Acid-Gas
Enhanced Oil Recovery in the Zama Oil Field in Northwestern Alberta, Canada
Reservoir Condition CO_2-Brine Drainage and Imbibition Relative Permeability Displacement Characteristics in the Zama Area, Muskeg Anhydrite Formation (Cap Rock)
Uniaxial, Triaxial, and Elastic Properties Determinations on Samples from the Zama Field, Northwest Alberta
Evaluation of Deep Wellbore Integrity In the Zama Field
Petrographic and Reservoir Quality Assessments Vol. I
Petrographic and Reservoir Quality Assessments Vol. II
Petrographic and Reservoir Quality Assessment, Dolostone and Limestone, Muskeg and Zama Formations 05-10-117-04W6

References

Apache Canada Ltd., 2003, Resource application for approval to implement an enhanced oil recovery scheme in the Zama Keg River F Pool using acid gas as a miscible flooding solvent: EUB Guide 65, Schedule 1.