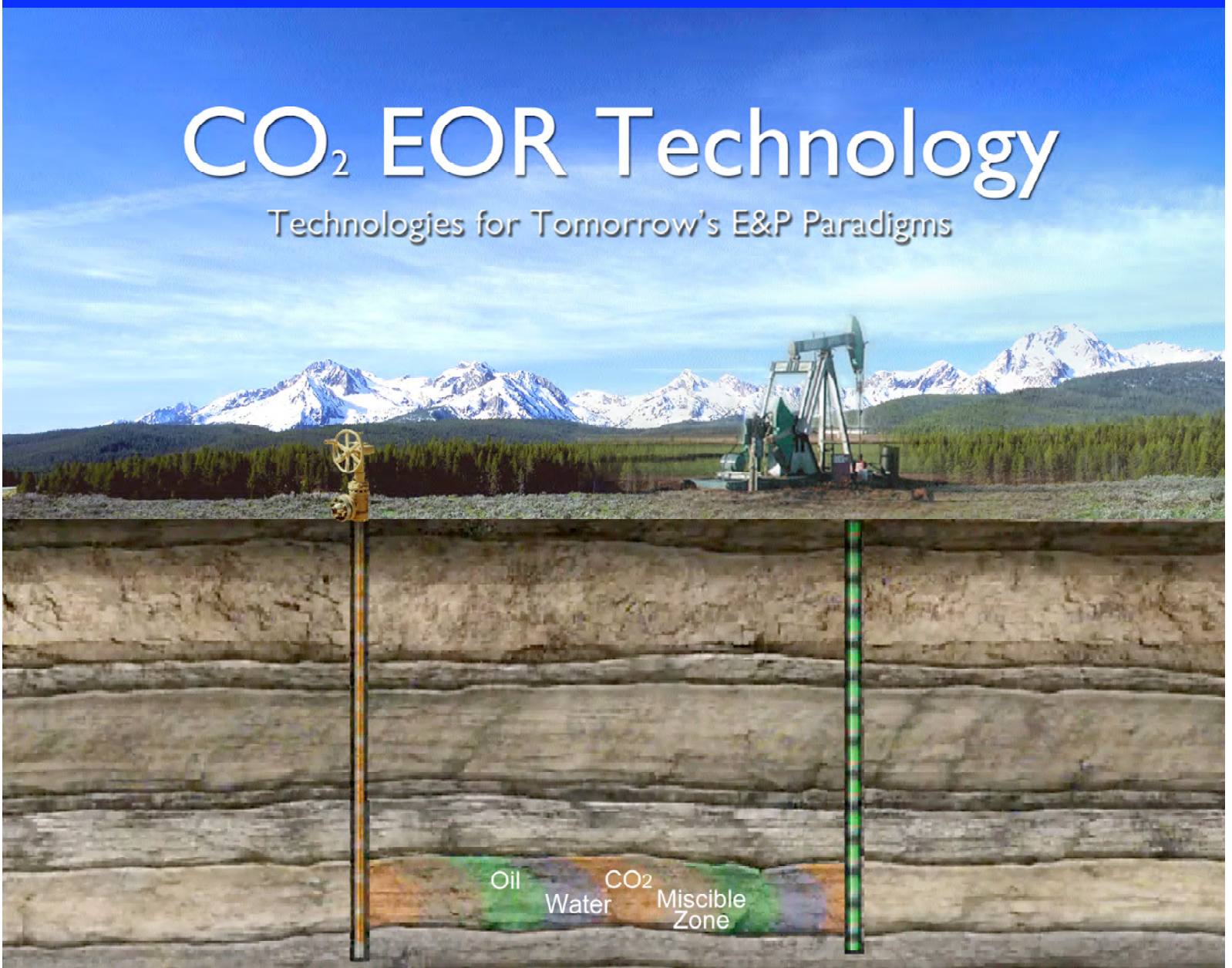
U.S. Department of Energy • Office of Fossil Energy
National Energy Technology Laboratory

CO_2 EOR Technology

Technologies for Tomorrow's E&P Paradigms



DOE R&D puts CO_2 EOR on verge of explosive growth

Economics, technology advances, environmental benefits align for growth opportunity

Technology advances, higher oil prices, reduced costs, and environmental needs have aligned to create a strong growth opportunity for a well-established method for enhancing oil recovery (EOR) in the United State: carbon dioxide (CO_2) flooding.

The U.S. Department of Energy is supporting critical research to help America's oil producers take full advantage of that growth opportunity.

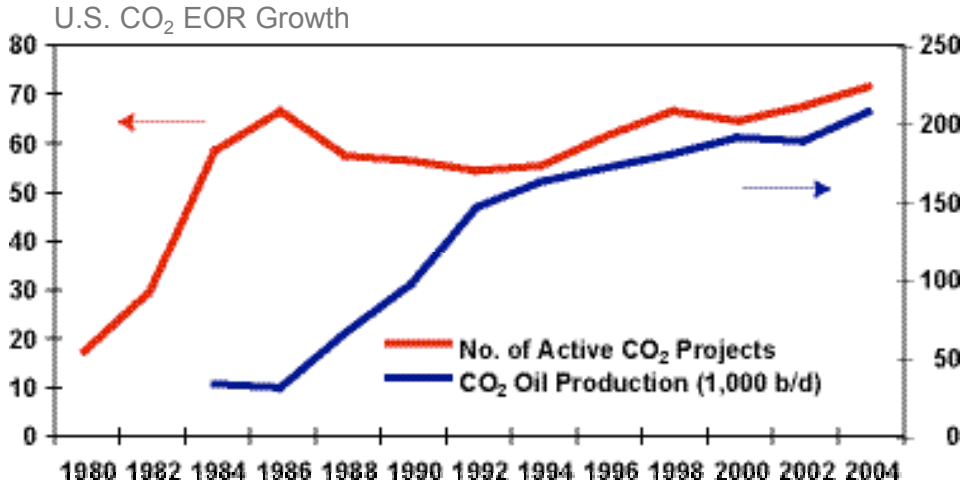
CO_2 flooding is the fastest-growing EOR technique in the United States. While production volumes and the number of projects for thermal, chemical, and other EOR processes have fallen off sharply since 1980, the number of CO_2 projects has more than tripled since 1980, to more than 70 projects as of yearend 2004. Meanwhile, CO_2 production volumes have jumped twenty-fold since the early 1980s (see chart). The CO_2 share of U.S. crude oil production was estimated at almost 206,000 barrels per day in 2004, according to the Oil & Gas Journal's biennial EOR Survey, last published April 12, 2004. That equals about 4% of the Nation's total.

Wider application

Commercial CO_2 flood projects in the United States largely have been limited to the prolific oil reservoirs of the Permian Basin of Texas and New Mexico that are especially amenable to this EOR process. Roughly half of the world's CO_2 floods are in the Permian basin, not far from some of the biggest natural sources of CO_2 in the U.S. Some industry estimates put incremental recovery from CO_2-floodable reservoirs in the Permian basin alone at 500 million to 1 billion barrels.

With the proper incentives and CO_2 availability to underpin an accelerated program, current technology applied to existing fields has the potential to double CO_2-enhanced oil production by 2015 and quadruple it by 2025, according to in-house modeling by DOE's National Energy Technology Laboratory (NETL).

CO_2 EOR's potential to boost U.S. oil production was further supported by a series of basin-oriented CO_2 EOR assessments that Advanced Resources International Inc. (ARI), Washington, DC, conducted for DOE's Office of Fossil Energy. Taken together, the assessments concluded that a broadly applied CO_2 flood campaign utilizing "state-of-the-art" CO_2 EOR technology in large, favorable reservoirs in these regions could add 88.7 billion barrels of *technically* recoverable crude to the Nation's potential oil supply portfolio. That's not the same as *economically* recoverable volumes, which hinge on oil prices, the ready availability of low-cost CO_2 supply, and other economic and technical risk factors. According to ARI's study, relying on "traditionally practiced" CO_2 EOR technology would enable just 4 billion barrels of this potential to be economic. However, introducing "state-of-the-art" technology with oil prices at $30-40 per barrel and large volumes of low-cost CO_2 readily available renders 24-40 billion barrels economically



Source: Oil & Gas Journal

Cover illustration adapted from an original image © John Perez Graphics & Design LLC

viable. By way of comparison, U.S. proved crude oil reserves total only 22.4 billion barrels. So finding the technology keys to support a widespread expansion of CO_2 flooding could mean a step-change in the volume of America's oil reserves and production.

In theory, there is good reason to believe that CO_2 flooding would work elsewhere in the United States. Past DOE research involved tests on most other kinds of reservoir rock. The upshot: CO_2 flooding could work in a wide range of reservoir types, as long as the effort can achieve a reasonable minimum miscibility pressure (MMP).

As early as the 1970s, DOE-funded projects were assessing the basic fluid properties of CO_2 regarding pressure, temperature, and oil composition. A special focus was given to developing MMP correlations, which helped the oil industry to prioritize these properties in order to implement commercial CO_2 projects successfully. During 1993-2003, DOE funded nearly half of the $100 million spent on Class Program CO_2 EOR field demonstration projects in six states, with a targeted incremental recovery of 23 million barrels of oil.

DOE-funded research continues to demonstrate the potential for technically and economically recovering crude oil from mature, domestic fields using available, state-of-the-art technologies in conjunction with CO_2 flooding. These technologies include horizontal wells for improved reservoir contact, 4-dimensional seismic to monitor the behavior of CO_2 floods, automated field monitoring systems for detecting problems, and injecting larger volumes of CO_2.

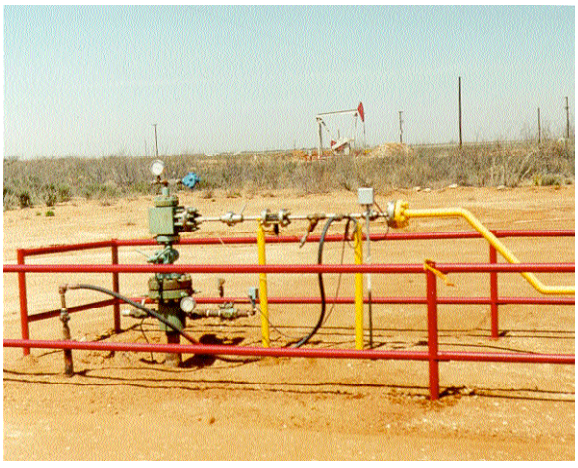
Emerging, advanced EOR technologies could have an even greater impact. Virtually all CO_2 flooding targets light oil reservoirs deeper than 3,000 feet. However, some DOE-funded research has ascertained that its solvent effect also reduces oil viscosity in reservoirs with heavier crudes. Coupled with the increased oil saturation identified with CO_2-induced swelling, this points to the suitability of CO_2 flooding for a range of reservoirs not typically amenable to miscible displacement processes.

Technology challenges

The major technical challenge isn't finding reservoirs amenable to CO_2 floods—it's being able to control proper mobility and proper sweep of the injected gas.

Most CO_2 floods entail injecting a large slug of CO_2 followed by injection of water—which drives the CO_2—to maximize sweep efficiency. Modifying CO_2 viscosity is critical because differences in CO_2 viscosity and density relative to the crude oil-in-place can set the stage for premature breakthrough of the gas. Such breakthrough results from a combination of gravity override and the CO_2 channeling through more-permeable zones. The end result is less oil ultimately recovered.

The response to this challenge entailed alternating injection of water and gas (WAG), which improved sweep efficiency. But this posed another problem: While sweep improves with WAG, displacement efficiency may decline because the water can shield the oil from the solvent-like nature of the gas. So DOE has funded much research on alternative ways to improve CO_2 sweep efficiency—with foams,



CO_2 injection well, with a pumpjack in the background, part of a CO_2 flood pilot project operated by Advanced Reservoir Technologies Inc. under subcontract from Occidental USA Inc. in Oxy's West Welch Unit in the Permian Basin of West Texas

chemical gels, and direct thickening agents. At present, the agency is funding the only U.S. public research on improving reservoir sweep by modifying CO_2 viscosity.

CO_2 Costs

Industry has been able to cut CO_2 operating costs by more than 50% since the early 1980s. Kinder Morgan CO_2 Co. L.P. estimates that overall operating costs have plunged to less than half the $1 million per flood pattern seen in the 1980s.

Meanwhile, CO_2 costs have fallen sharply as interest in the technology has grown. Kinder Morgan estimates that CO_2 prices have dropped by 40%. The company, the leading provider of CO_2 to EOR projects, estimates total operating expenses exclusive of CO_2 costs at $2-3 per barrel.

In addition, once a flood is under way, the produced CO_2 can be captured and recycled. This all adds up to a project that can yield a healthy profit even if oil prices are as low as $18 per barrel, says Kinder Morgan.

Environmental benefits

The attractiveness of CO_2 EOR gains added luster when potential environmental benefits are factored in.

Utilizing an industrial source of CO_2 for EOR costs more than using natural sources, but this approach adds the benefit of capturing and sequestering CO_2 emissions. DOE is funding research related to this concept: a field demonstration project involving a CO_2 miscible flood in central Kansas that utilizes a CO_2 stream from a nearby ethanol plant.

Because there are no natural sources of CO_2 available nearby, no one has attempted a commercial CO_2 flood in a Kansas oil field to date. Early results are promising, and if this approach can be applied to other Kansas fields, the incremental oil production resulting from CO_2 floods in that state ultimately could total 600 million barrels.

At the same time, capturing the ethanol plant's waste CO_2 and safely storing it—"sequestering" the CO_2—reduces emissions of the predominant greenhouse gas. Such an effort to capture industrial CO_2 and utilize in EOR projects could be multiplied many times over across the country, adding up to significant impacts in terms of increased U.S. oil production and reduced CO_2 emissions. That realization helped spur a major new DOE funding solicitation (see related story on p. 5).

Supply issues

Many analysts believe a new, higher range for oil prices could persist indefinitely—perhaps permanently.

Meanwhile, DOE's Energy Information Administration forecasts steadily rising demand for oil and steadily declining crude oil production in the U.S. The nation's dependence on imported oil, as a result, could soar to 70% by 2025, EIA projects.

It follows, then, that DOE deems research into CO_2 EOR, a technology with such a strong potential for widespread commercial application, to be a crucial part of its fossil energy mission in the new millennium.

Energy security, economic, and environmental benefits add up to a compelling case for championing the spread of CO_2 EOR technology across the Nation. And that dovetails neatly with DOE's oil and gas research mission.

This pumpjack in Hall-Gurney oilfield, together with the ethanol plant in the background near Russell, KS, demonstrate the synergistic environmental and energy benefits of using industrial waste carbon dioxide in a CO_2 flood.

DOE launches CO_2 EOR/sequestration initiative

The Department of Energy has launched a solicitation to fund new research in technologies that entail injecting carbon dioxide (CO_2) to boost recovery of the Nation's oil and natural gas resources while also serving to safely store CO_2, rather than emit the greenhouse gas into the atmosphere.

As the fastest-growing technique for enhanced oil recovery (EOR), CO_2 flooding now accounts for 4% of the Nation's oil production. Flooding a natural gas reservoir with CO_2 moves previously bypassed natural gas to producing wells by pressurizing and/or displacing it—although this enhanced gas recovery (EGR) technique is not widely used.

An EOR or EGR project that uses an industrial source of CO_2—that otherwise would be vented to the atmosphere—would have the added environmental benefit of capturing and safely storing, or "sequestering," the CO_2, the predominant greenhouse gas. DOE currently is funding one such project, the first CO_2 flood in Kansas, which gets its CO_2 from a nearby ethanol plant.

The DOE solicitation supports producers of oil and gas in carrying out EOR/EGR projects to inject CO_2 in order to improve oil or gas recovery while increasing sequestration of CO_2. The solicitation provides up to $3,000,000 per project in federal funds to operators who will field-test and validate integrated enhanced recovery/sequestration technologies. Projects may last 2-5 years and require a 50% cost share by the recipient.

The projects will be managed through DOE's National Energy Technology Laboratory (NETL), America's only National Laboratory devoted to fossil energy research.

Driven by a mandate of the 2005 Energy Policy Act, the solicitation seeks to maximize U.S. oil and natural gas production in a cost-effective manner through the injection of CO_2, while at the same time sequestering significant quantities of CO_2. This solicitation provides a bridge between reducing greenhouse gases from industrial waste streams and the beneficial use of CO_2 injection for increasing oil and gas recovery.

Fossil fuel-fired power plants and other industrial producers of waste CO_2 could find an attractive business opportunity in sequestering their greenhouse gas emissions by selling the waste CO_2 to oil and gas field operators for enhanced recovery. Oil and gas fields' capacity for sequestering CO_2 is enormous. One study conducted for DOE estimated that the global sequestration capacity in depleted oil and gas fields equates to 125 years of current worldwide CO_2 emissions from fossil fuel-fired power plants.

As pressure builds to reduce CO_2 emissions amid concerns over postulated climate change, future CO_2 sequestration efforts are likely to be met with incentives such as fiscal relief or emissions trading credits. That could help level the playing field between natural and industrial sources of CO_2. Broadening use of industrial CO_2, in turn, could expand the applicability of CO_2 EOR/EGR to other areas of the United States while "closing the carbon cycle." A widespread campaign of CO_2 EOR across the U.S. could ensue, if operators could obtain CO_2 from industrial sources, such as power plants, at a reasonable cost.

In doing so, this two-pronged technology initiative serves two key goals of President Bush's National Energy Plan: increasing domestic energy supply while protecting the environment.

Proposers should apply through **http://www.grants.gov**. This website contains information, application forms, and instructions for this solicitation, as well as other DOE funding opportunities.

PROJECT facts

U.S. Department of Energy
Office of Fossil Energy
National Energy Technology Laboratory

Time-Lapse Seismic Modeling and Inversion of CO_2 Saturation for Sequestration and Enhanced Oil Recovery

DE-FC26-03NT15417

PARTNER

4th Wave Imaging Corp.
Aliso Viejo, CA

MAIN SITE

Aliso Viejo, CA

Background/Problem

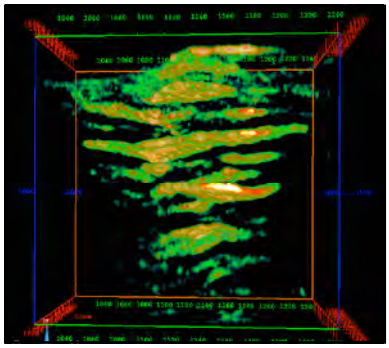
Time-lapse seismic monitoring during CO_2 injection is still in its infancy. Seismic monitoring requires knowledge of the rock and fluid properties of the oil reservoir to track changes in CO_2 saturation and pressure over time. In addition, the behavior of supercritical CO_2 is complex, and its interaction with brine and oil in porous rock systems is not well understood. Modeling CO_2 behavior can often lead to numerical instabilities that can create large artifacts in modeled time-lapse seismic data and maps of CO_2 saturation and pressure changes.

Description

The goal of this project is to improve current methods of rock physics and time-lapse seismic reflection modeling for CO_2 sequestration and miscible CO_2 floods in oil and gas reservoirs, and to develop new strategies to invert such data to estimate changes in pressure, oil saturation, water saturation, and CO_2 saturation over time.

The project consists of three phases. In Phase I new ways to calculate fluid properties of oil-water-CO_2 mixtures under varying reservoir conditions are being investigated. A thorough literature search has revealed two major approaches for accomplishing this, using either an equation-of-state (EOS) formulation or molecular dynamics simulations. These two approaches are being compared for robustness and accuracy. A preliminary EOS formulation has been developed that is capable of generating bulk fluid properties from multiple liquid and gas phases for supercritical CO_2 mixtures.

In Phase II this EOS is being used to perform 1-D time-lapse seismic modeling by calculating changes in well-log velocities and densities under varying CO_2 saturations and pressures. In addition, progress has been made in building a 3-D seismic modeling tool that can be used to predict time-lapse seismic anomalies in 3-D field data. In Phase III, a method is being developed to invert time-lapse seismic anomalies to yield maps of CO_2 saturation and pressure changes over time. Researchers have completed the first step of this method, which generates seismic attributes as a function of CO_2 saturation and pressure changes, including changes in both miscible and free CO_2 levels.



3-D perspective of seismic-reflection amplitudes from the 2002 Sleipner North Sea data set. Clouds of high-amplitude values delineate the location and extent of the CO_2-saturated zones within the Utsira sand.

Accurate modeling methods enable high-resolution CO_2 flood front imaging

CONTACT POINTS

Roy Long
Technology Manager
U.S. DOE
918-699-2017
roy.long@netl.doe.gov

Purna Halder
Project Manager
U.S. DOE
918-699-2084
purna.halder@netl.doe.gov

Mark Meadows
Principal Investigator
4th Wave Imaging Corp.
949-916-9787
mark.meadows@4thwaveimaging.com

TOTAL ESTIMATED COST

$0.8 million

COST SHARING

DOE	$0.6 million
Non-DOE	$0.2 million

PROJECT START/END

Start	September 30, 2003
End	March 31, 2006

WEBSITE

www.netl.doe.gov

Accomplishments

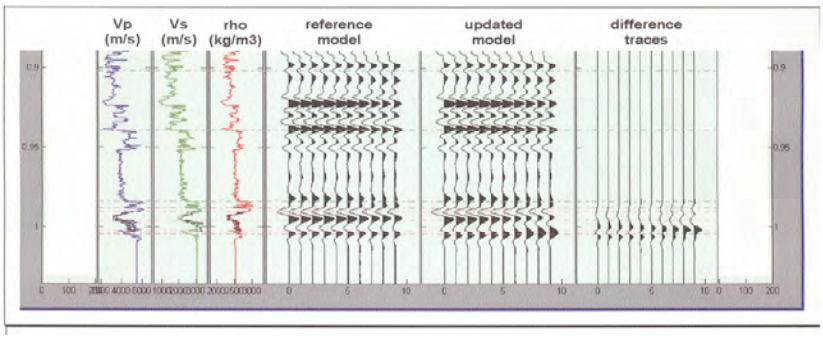
This project has resulted in new algorithms to accurately model time-lapse seismic changes during CO_2 injection and to invert these data to estimate changes in reservoir properties, such as pressure and CO_2 saturation, that cause the seismic anomalies. Both modeling and inversion algorithms rely on rock physics relations to estimate seismic parameters, such as velocities and densities, as a function of CO_2 saturation and pressure. Among the major achievements of this project, researchers have:

- Investigated new ways to compute fluid properties of oil-water-CO_2 mixtures using both EOS methods and molecular dynamics modeling.
- Wrote a 1-D seismic modeling program that uses time-lapse changes in well-log velocities and densities to predict changes in seismic data during CO_2 injection.
- Wrote an algorithm to accomplish the first step of the inversion procedure, namely, the generation of time-lapse seismic attribute changes as a function of changes in CO_2 saturation and pressure.
- Completed a preliminary evaluation of time-lapse seismic anomalies in different vintages of the Sleipner North Sea 3-D data set.

Benefits/Impacts

CO_2 is widely viewed as an important agent in global warming. In addition, miscible CO_2 flooding has become an increasingly important enhanced oil recovery (EOR) method for recovering residual or bypassed oil. For example, roughly half the CO_2 floods in the world are located in the Permian Basin, accounting for more than 20% of the area's total oil production.

By developing an accurate approach for tracking CO_2 fronts during EOR operations, this project is expected to help improve recovery rates, optimize well patterns, locate bypassed oil, and minimize the cost of injected CO_2. Project results will also benefit the public by improving current methods for monitoring reservoir leaks and verifying the location and quantity of sequestered CO_2 in order to minimize its emission.



Example of time-lapse seismic modeling of well-log velocities and densities during CO_2 injection.

PROJECT facts
U.S. Department of Energy
Office of Fossil Energy
National Energy Technology Laboratory

Demonstration of a Novel, Integrated Multi-Scale Procedure For High-Resolution 3-D Reservoir Characterization and Improved CO_2 EOR/Sequestration Management, SACROC Unit

DE-FC26-04NT15514

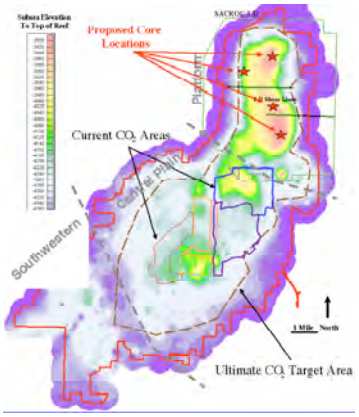
PARTNERS

Advanced Resources International, Inc.
Houston, TX

Kinder Morgan CO_2 Company, LP
Midland, TX

MAIN SITE

Kelly-Snyder field
West Texas



Map of SACROC Unit showing proposed core locations in Northern Platform area.

Background/Problem

Discovered in 1948, the Kelly-Snyder oilfield of West Texas covers an area of about 50,000 acres with an estimated original-oil-in-place (OOIP) of 2.8 billion barrels. The field can be divided into three broad regions: the Northern Platform, Central Plain, and the Southwestern area. The SACROC Unit was formed in 1952 to facilitate coordinated water-flooding of the field. CO_2 EOR began in 1972 and has traditionally been focused in the Central Plain, where reservoir architecture is amenable to pattern flooding. The Northern Platform area contains the thickest interval, however, ranging from 80 feet at the periphery to more than 750 feet at the center, and contains the greatest concentration of oil resource. Geologic and production data from this area suggest it may be a potential candidate for gravity-stable CO_2 EOR. Kinder Morgan, the operator of the unit, is evaluating the feasibility of gravity-stable CO_2 EOR for the SACROC Unit Platform area.

Description

The goal of this project is to demonstrate the application and benefits of data-driven modeling for multi-scale data integration for high-resolution 3-D reservoir characterization to better address management of CO_2 EOR floods and carbon sequestration projects.

The approach being demonstrated in this project utilizes advanced pattern-recognition technologies (self-organizing maps, artificial neural networks, and fuzzy logic) to establish relationships between data at different scales, and by doing so, creating a "transform" to derive core-scale reservoir properties from 3-D surface seismic data.

This approach can overcome the shortcomings of current industry practices by:

- Utilizing intermediate frequency data, specifically crosswell seismic to bridge the resolution gap between surface seismic and geophysical well logs such that the resulting transform is more constrained.
- Incorporating core data such that the result is provided in terms of the reservoir engineering parameters needed for effective reservoir management.
- Using the increasing elastic frequency of each data type to deconvolve the surface seismic to a higher resolution.
- Doing so in a relatively direct manner, with common computing tools.

Data driven modeling for multi-scale data integration

This project takes advantage of the intense data-collection efforts planned by Kinder Morgan for an assessment of gravity-stable CO_2 EOR for the SACROC Unit Platform area. This includes the collection of core over the entire reservoir interval at up to four locations in the Platform area and a foot-by-foot analysis for reservoir properties, including porosity and multi-azimuth permeability, geophysical well logs, and crosswell seismic surveys. (A 3-D surface seismic survey already exists over the entire area.)

Advanced Resources International will use these data to develop a high-resolution seismic-to-core transform and apply it to a selected portion of the field for validation. Validation will be performed by independently testing the existence and properties of vertical flow barriers in the reservoir section in one or more well locations (vertical interference testing) and comparing those results with the predictions based on the new reservoir characterization procedure

CONTACT POINTS

Roy Long
Technology Manager
U.S. DOE
918-699-2017
roy.long@netl.doe.gov

Daniel Ferguson
Project Manager
U.S. DOE
918-699-2047
daniel.ferguson@netl.doe.gov

Scott R. Reeves
Principal Investigator
Advanced Resources International Inc
713-780-0815
sreeves@adv-res-hou.com

TOTAL ESTIMATED COST

$10.0 million

COST SHARING

DOE	$5.0 million
Non-DOE	$5.0 million

PROJECT START/END

Start	September 20, 2004
End	March 31, 2007

WEBSITE

www.netl.doe.gov

Accomplishments

Preliminary research was done to compare advantages and drawbacks of various data-driven modeling techniques currently utilized in reservoir characterization tasks. A model-based neural system has been adopted. The mathematical framework of this system is called Maximum Likelihood Adaptive Neural System; it is a neural system that combines *a priori* knowledge, adaptability, and fuzzy logic.

Statistical analysis of geophysical well logs has been done to provide summary descriptions, cross-information, and detection of trends, correlations, and possible anomalies.

Pattern recognition procedures have been applied in a cored well to produce preliminary rock-type classifications and to test the influence capacity of different types of geophysical well logs.

Benefits/Impacts

Oil reserves in the Permian Basin are estimated at 4.2 billion barrels. If the proposed technology can be applied to only 5% of the reservoirs that correspond to this reserve estimate and can improve recovery on average by 25% (i.e., improving recovery from 40% to 50% of OOIP), the technology developed in this project would facilitate the recovery of 53 million barrels of additional oil. At a market price of $50/bbl, an increase in economic activity of $2.65 billion would result. If the local, state, and federal government share of that economic activity were 20% (i.e., production taxes, employment taxes, income taxes, etc.), the government share would be $530 million. Even if substantially reduced by the application of risk factors, the potential payoff for the project, for industry and government alike, is highly attractive.

SACROC Unit #19-12 well (June 26, 2005).

PROJECT facts

U.S. Department of Energy
Office of Fossil Energy
National Energy Technology Laboratory

Oil Reservoir Characterization and CO_2 Injection Monitoring in the Permian Basin with Crosswell Electromagnetic Imaging

DE-FC26-00BC15307

PARTNERS

ElectroMagnetic Instruments, Inc.
Richmond, CA

Lawrence Livermore National Laboratory
Livermore, CA

Geo-BILT
Richmond, CA

ChevronTexaco Corp.
San Francisco, CA

Schlumberger Ltd.
Houston, TX

MAIN SITES

EMI Test Site
Richmond, CA

Lost Hills field
Kern County, CA

Kern River field
Kern County, CA

Vacuum field
Lea County, NM

Crosswell receiver being prepared to lower in wellbore.

Background/Problem

Crosswell electromagnetic imaging technology, based on earlier radar imaging technology, will help interpret the reservoir rock and fluid flow through the reservoir between wells. The necessary resolution to accurately map fluid properties has been missing from conventional seismic analysis.

Crosswell EM imaging is designed to give accurate measurement of oil saturations in the areas between wells. Previous logging techniques could only generate oil saturation data close to the wellbore. Crosswell EM logging can provide the operator with an actual image of fluid migration and show where specific areas of undeveloped reservoir remain.

Description

The Crosswell Electromagnetic Imaging Tool was developed at Lawrence Livermore National Laboratory (LLNL) from 1991 to 2000. ElectroMagnetic Instruments, Inc. (EMI) was created by former LLNL scientists to further the research and commercialization of the Crosswell Electromagnetic Imaging downhole logging tool. EMI developed a five-well pattern test site in Richmond, CA, to continue testing and construction of the tool prior to commercial field tests.

Crosswell electromagnetic logging involves the use of a string of receivers in one well and a transmitter lowered into a neighboring wellbore. The development of sensitive receivers, advanced transmitters, and fiber optics was an essential part of the implementation of crosswell logging, and these advances have been incorporated into the development of the EM extended-logging tool. The DOE project has refined transmitter and geophone receiver design and deployed the EM tool in uncased, fiberglass-cased, and steel-cased wellbores.

EM logging depends on interpretation of three components: compressional, vertical shear, and horizontal shear waves between transmitter and receiver. Using a multiple array of receivers and moving the transmitter up and down in the neighboring well allows imaging of a roughly elliptical region between the wells. Several transmitter-receiver combinations are used per survey to gather data. Currently, EM logging of a 1,000-foot section of an uncased wellbore can be accomplished in 12 hours. The logging tool can be used in uncased and fiberglass-cased wells with no difficulty, and has been successfully demonstrated when one well of a pair is steel-cased. Steel casing significantly slows transmission time and interferes with the signals.

Improved crosswell logging applicable to CO_2 flooding

Accomplishments

The first field applications of crosswell EM logging were conducted in 1997-98. A crosswell survey was conducted at Kern River oilfield in California in 1998 to map the residual oil saturation and determine which factors controlled steam and oil flow in the heavy oil reservoir. Identification of the steam path allowed redesign of the steamflood to produce unswept areas. Crosswell imaging applied at Lost Hills field in California in 1997-98 imaged the waterflood performance of the Belridge Diatomite. Chevron USA Inc. used two fiberglass-cased wells to observe the results of water injection in this fractured reservoir. Imaging resistivity changes over time demonstrated that crosswell data could be used to map migration of the waterflood front, providing an excellent means for understanding reservoir dynamics and optimizing the oil recovery process of the waterflood.

The Geo-BILT tool, a modified prototype EM imaging tool designed and tested by EMI, successfully demonstrated that multicomponent logging was applicable in several different geological environments. Geo-BILT has the advantage that it is capable of single-well extended logging. The tool uses a transmitter situated 3 meters above the receivers on a line and provides a 3-D image of the wellbore area up to a radius of 50 to 250 meters. Single-well logging will significantly reduce logging cost while providing critical reservoir data.

Crosswell electromagnetic imaging was used to monitor CO_2 injection performance in New Mexico's Vacuum field, operated by ChevronTexaco. This 3-year DOE project involved development of crosswell EM dual-steel casing logging tools, software development, data processing, and imaging of low-induction frequencies. The results were used to develop resistivity models showing the distribution, size, and depth of the low-resistivity zones, which could be correlated to interwell CO_2 migration.

Benefits/Impacts

Crosswell EM imaging has been demonstrated successfully for use in monitoring steamfloods, waterfloods, and CO_2 floods. Crosswell EM imaging was proved to be 10 times more effective than the previous logging techniques used at Vacuum field to monitor CO_2 flooding. Information obtained from EM surveys will allow field operators to optimize production and produce more oil in a cost-effective manner. The progress of imaging through fiberglass and steel casing will increase significantly the application of the technique in regions where uncased wells cannot be used. The newest advances in single-wellbore imaging holds great potential for use in offshore drilling, where the expense of idling wells for logging procedures will be reduced by cutting the number of wells necessary to complete the EM survey.

Following successful demonstrations of the tool's effectiveness, specifically single-borehole imaging, imaging through steel casing, and CO_2 monitoring, EMI was purchased by Schlumberger Ltd., a major oilfield service company. Schlumberger is backing the continued development and implementation of the Crosswell EM tool with a capital investment of $15 million, indicating its confidence that crosswell EM logging tools have a secure place in the future of the petroleum industry.

CONTACT POINTS

Roy Long
Technology Manager
U.S. DOE
918-699-2017
roy.long@netl.doe.gov

Paul West
Project Manager
U.S. DOE
918-699-2035
paul.west@netl.doe.gov

Michael Wilt
Principal Investigator
ElectroMagnetic Instruments, Inc.
519-232-7997
mwilt@eminc.com

Phil Harben
Lawrence Livermore
National Laboratory
925-422-3571
harben1@llnl.gov

TOTAL ESTIMATED COST

$1.2 million

COST SHARING

DOE	$0.8 million
Non- DOE	$0.4 million

PROJECT START/END

Start	September 11, 2000
End	August 2, 2004

WEBSITES

www.netl.doe.gov
www.emiinc.com

PROJECT facts

U.S. Department of Energy
Office of Fossil Energy
National Energy Technology Laboratory

Technology Development and Demonstration of Microhole Oil Production / Microholes for Designer Seismic in Support of CO_2 EOR

FEW03FE06-04/
FEW03FE06-06

PARTNERS

Los Alamos National Laboratory (LANL)
Los Alamos, NM

Lawrence Berkeley National Laboratory (LBNL)
Berkeley, CA

Dennis Tool Company
Houston, TX

Quality Tubing
Houston, TX

Rocky Mountain Oilfield Testing Center (RMOTC)
Casper, WY

MAIN SITE

Naval Petroleum Reserve No. 3
Casper, WY

LANL microdrilling at the RMOTC-operated Teapot Dome Field at NPR No. 3.

Background/Problem

LANL's experience with seismic data acquisition in oilfields indicates that low-cost, dedicated microholes for deployment of seismic sensors are needed to enhance acoustic data monitoring of the subsurface. Dedicated data acquisition holes provide reduced natural surface and cultural noise, reduced or eliminated seismic-signal travel paths through highly attenuating surface layers, and a greatly improved signal-to-noise ratio.

Accordingly, microholes promise a low-cost alternative to conventional wells; they can be placed in the desired location and designed for optimal acquisition of seismic data.

The primary goal of the first project is to show that microholes provide downhole access at significantly lower cost than conventional wells and provide superior acoustic performance when compared with the use of temporarily converted production or injection wells. The second—and related—project's goal is to adapt microhole systems for deploying microseismic arrays in CO_2 enhanced oil recovery operations.

Description

Project researchers are demonstrating the technical and economic feasibility of developing a highly mobile, self-contained, microhole drilling system for seismic data acquisition and other applications.

LANL is evaluating commercial equipment with the potential to enhance the performance of microdrilling. Two demonstrations are ongoing with good early results: Quality Tubing Inc.'s QT16Cr80 stainless steel coiled tubing (CT) as a drill stem for microdrilling and Dennis Tool Company's low-torque, low weight-on-bit drilling assembly.

Work in FY 2006 (project number FEW03FE06-06) includes the completion of up to 6 microholes at two CO_2 EOR injection sites to monitor CO_2 injection. The 500-1,500-foot microwells will be designed to support the deployment of seismic arrays by LBNL. The LANL drilling team will collaborate with LBNL, the commercial field operators, and project reservoir specialists to drill and complete microholes to optimize the collection of seismic data to monitor an active CO_2 injection process.

Small-diameter instrumented wells expected to enable CO_2 injection monitoring

CONTACT POINTS

Roy Long
Technology Manager
U.S. DOE
918-699-2017
roy.long@netl.doe.gov

Daniel Ferguson
Project Manager
U.S. DOE
918-699-2047
daniel.ferguson@netl.doe.gov

Don Dreesen
Principal Investigator
LANL
505-667-1913
dreesen@lanl.gov

TOTAL ESTIMATED COST

$1.9 million

COST SHARING

DOE	$1.3 million / $0.6 million
Non-DOE	$0 / $0

PROJECT START/END

Start	Mar. 15, 2003 / Feb. 15, 2006
End	Mar. 14, 2006 / Feb. 14, 2007

WEBSITE

www.netl.doe.gov

Accomplishments

The LANL drilling team has successfully demonstrated CT-deployed microdrilling in wells as small as 1¾-inch diameter and as deep as 1,300 feet in soft sediments and unconsolidated formations. LBNL demonstrated the use of microholes for acquisition of high-quality vertical seismic profile data. In a recent microdrilling field demonstration at the RMOTC site, LBNL successfully fielded geophysical instrumentation in LANL completed microholes cased with both 1.660-inch PVC and steel tubing.

The LANL CT unit was modified to increase the maximum microhole depth from 800 feet to 1,500 feet and increase the maximum drilling-fluid circulation pressure from 2,000 psi to 5,000 psi. A microhole was drilled to 1,310 feet, and a high-performance drilling assembly was operated at 3,500 psi maximum mud-pump pressure. The CT reel was modified to accommodate an additional 700 feet of coiled tubing.

Benefits/Impacts

Micro-instrumentation holes could cost as little as a quarter to a tenth that of conventional boreholes. Successful demonstration of a nonmetallic casing such as PVC line pipe may reduce acoustic noise and improve the performance of micro-instrumentation holes dedicated to reservoir-monitoring service.

David Anderson (left) and Mike Fehler (right), LANL Geophysics Group Technician and Group Leader, respectively, on a Teapot Dome microwell drilling location with the LANL coiled tubing unit in the immediate background and the blue mud-cleaning unit behind the coiled tubing unit.

PROJECT facts

U.S. Department of Energy
Office of Fossil Energy
National Energy Technology Laboratory

Implementing a Novel Cyclic CO_2 Flood in Paleozoic Reefs

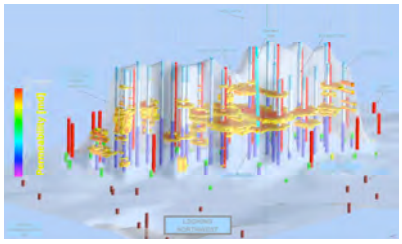
DE-FG26-02NT15441

PARTNER

Michigan Technological University
Houghton, MI

MAIN SITE

Dover field
Otsego County, MI



Visualization of a Belle River Mills reef showing core permeability voxels.

Background/Problem

The Michigan Basin contains over 700 reef fields that have produced over 300 million barrels of oil and 2 trillion cubic feet of gas. Most of these wells are now shut-in or plugged and abandoned, even though the primary recoveries were only 25-40%. These reefs are valuable resources and obvious targets for enhanced recovery. Few enhanced recovery projects have been implemented, even though many of them may produce hydrocarbons nearly equal to the original primary recovery, in some cases an additional 250,000-500,000 barrels of oil per reef.

Two CO_2 projects in the Michigan pinnacle reefs have reported incremental production of 160,000 and 430,000 barrels. Those volumes represent 14% and 33%, respectively, of the primary recovery produced in just 5 years. One of the projects, at Dover field in Otsego County, is close this project's proposed demonstration well. Data released to the State of Michigan indicate that the CO_2 flood restored the production to nearly initial conditions. However, the details of the operations have not been made public, and this has been a serious impediment to widespread adoption of the technology.

Description

Pinnacle reefs have a high vertical relief and are nearly hermetically sealed. CO_2 was injected into the top of the reef, and the hydrocarbons were collected from a horizontal drain well drilled at the base of the reef.

The CO_2 was obtained from nearby natural gas wells producing from the Antrim Formation, where the gas was compressed and dehydrated, then piped a short distance (1 mile) to the demonstration well. There it was injected to bring the reef back to nearly virgin pressure, and the remobilized hydrocarbons migrated to the bottom of the reservoir as the gas cap expanded.

Nearby well logs that penetrate the reef were analyzed using a new approach that has been developed at Michigan Technological University. This approach has been termed Log Curve Amplitude Slicing (LCAS) and uses suites of well logs to map the horizon of interest at 1-foot intervals, essentially utilizing the full information content of the log. The technique is similar to mapping formation tops from log picks or drillers' reports, except that the attribute is mapped at much more closely spaced intervals (e.g., 1 foot).

Visualization of reservoir parameters increases hydrocarbon recovery in mature pinnacle reefs

Injection of CO_2 into one recompleted well began in May 2004. In July 2004 a second well was recompleted as an injector. Initial production response showed an increase from 9 barrels of oil per day to 90 barrels of oil per day. The researchers' industry partners are optimistic that the producing well may actually transition from pumping to flowing as reservoir pressure increases as a result of CO_2 injection.

CONTACT POINTS

Roy Long
Technology Manager
U.S. DOE
918-699-2017
roy.long@netl.doe.gov

James Wood
Principal Investigator
Michigan Tech. University
906-487-2894
jrw@mtu.edu

TOTAL ESTIMATED COST

$2.2 million

COST SHARING

DOE	$1.1 million
Non- DOE	$1.1 million

PROJECT START/END

Start	September 25, 2002
End	December 31, 2005

WEBSITE

www.netl.doe.gov

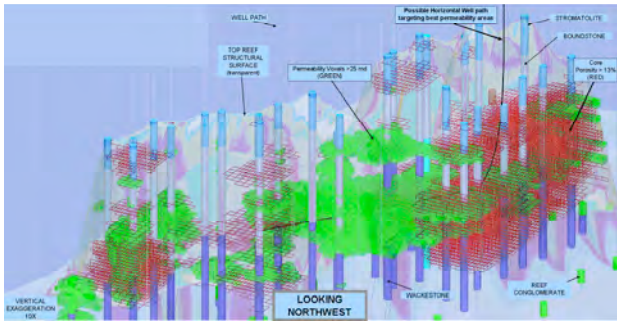
Accomplishments

A production response of more than 80 barrels of oil per day resulted from the initial stage of repressurization of a depleted Niagaran pinnacle reef using Antrim waste CO_2. Detailed reservoir modeling of Niagaran reefs using the technique of well log tomography is producing a new reservoir characterization tool that can be used for the visualization of permeability and porosity distribution in oil and gas reservoirs.

Benefits/Impacts

The project demonstrated a simple operation that can be widely implemented at a relatively low cost. It is expected that a demonstration well in Otsego County, MI, will produce an additional 400,000-600,000 barrels of oil—almost equaling the original primary production—and at that rate will be economic. Estimated costs to acquire, compress, and inject the CO_2 and recover the oil total about $3 million. The break-even point would be at about 75,000 barrels, assuming $40/barrel oil.

An extensive belt around the northern and southern margins in Michigan has proven reef production, with over 700 reefs discovered. Assuming that 100 reefs could be candidates for CO_2 injection and assuming an average recovery of 400,000 barrels, the basin-wide recovery potential approaches 40 million barrels. For this project, about 17 reefs and 130 wells have been identified in the vicinity of the proposed demonstration well. This region was evaluated for enhanced recovery potential as part of this project.



Visualization of a Belle River Mills reef showing permeability voxels >25md (green) and >13md (red).

PROJECT facts

U.S. Department of Energy
Office of Fossil Energy
National Energy Technology Laboratory

Improving CO_2 Efficiency for Recovering Oil in Heterogeneous Reservoirs

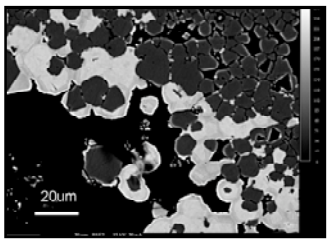
DE-FC26-02BC15364

PARTNER

New Mexico Petroleum Recovery Research Center (PRRC)
New Mexico Institute of Mining and Technology
Socorro, NM

MAIN SITE

New Mexico Petroleum Recovery Research Center (PRRC)
New Mexico Institute of Mining and Technology
Socorro, NM



Scanning electron microscopy results of limestone core cross sections identify precipitation (lighter zones) that results in decreased permeability and thus injectivity reduction.

Background/Problem

Despite favorable characteristics of CO_2 for enhanced oil recovery, CO_2 floods frequently experience poor sweep efficiency caused by gas fingering and gravity override exacerbated by reservoir heterogeneity. Also, low productivity results from lower-than-expected injectivity. Poor sweep efficiency results from a high mobility ratio caused by the low viscosity of high-density CO_2 compared with that of water or oil. The effectiveness of water injection alternating with gas (WAG), a common process used for mobility control during CO_2 floods, is reduced by gravity segregation between water and CO_2 and amplified by permeability differences. Foaming agents have been introduced in the aqueous phase to control mobility. However, costs incurred by the loss of expensive chemicals to adsorption on reservoir rock often exclude this potentially beneficial option for many well operators.

This project benefits from previous DOE-funded CO_2 research projects at PRRC that have resulted in 40 publications on topics including injectivity, phase behavior and multiphase flow, pressure effects, mobility control and foam properties, selective mobility reduction, foam mechanisms, mixed surfactants and sacrificial agents, gravity drainage, imbibition, interfacial tension, field foam modeling and history matching, numerical methods, and CO_2 reservoir injection studies.

Description

The current project focuses on determining the mechanisms of adsorption and desorption of surfactants in a reservoir, the effects of reservoir conditions on surfactant solution/CO_2 foamability, and the causes of injectivity changes in CO_2 injection systems. The objectives are to increase effectiveness and viability of CO_2 mobility control using foaming systems, to minimize injectivity losses, and to model these mechanisms. This will result in improved understanding of foaming agents and injectivity. Most of the study was laboratory-related, coupled with supporting modeling and field liaison projects.

Project participants developed systems with low concentrations of good foaming agents that will reduce cost. These systems are derived using a sacrificial agent or a co-surfactant that shows synergistic improvements when mixed with the good foaming agents.

Research into improved CO_2 mobility control

CONTACT POINTS

Roy Long
Technology Manager
U.S. DOE
918-699-2017
roy.long@netl.doe.gov

Paul West
Project Manager
U.S. DOE
918-699-2035
paul.west@netl.doe.gov

Reid Grigg
Principal Investigator
PRRC
505-835-5403
reid@prrc.nmt.edu

TOTAL ESTIMATED COST

$1.5 million

COST SHARING

DOE	$1.0 million
Non-DOE	$0.5 million

PROJECT START/END

Start	September 28, 2001
End	September 27, 2005

WEBSITE

www.netl.doe.gov

Accomplishments

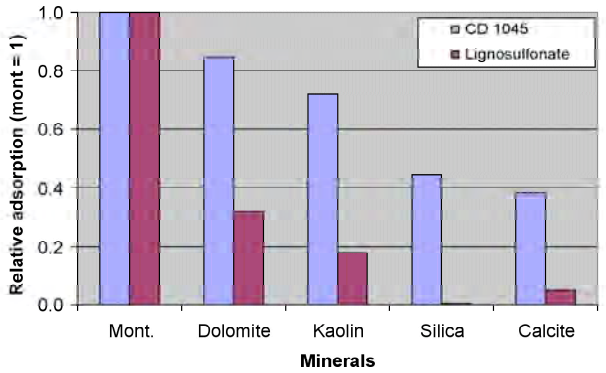
Project researchers have achieved the following milestones/insights:

- WAG coreflood experiments conducted on limestone and dolomite core plugs confirmed that carbonate mineral dissolution and deposition can occur over relatively short time periods (hours to days) and in close proximity to each other.
- Two series of core experiments, with nitrogen (N_2) and with CO_2 injected through core samples, indicate that although the Forchheimer equation is useful in describing high-velocity flow in porous media, in many cases it is not sufficient.
- Results of high-pressure/high-temperature/high-velocity gas flooding experiments on five different rock samples (sandstones and carbonates) under reservoir conditions reconfirm—and extend to new conditions—that permeability increases, while the non-Darcy flow coefficient decreases with increasing effective stresses; both are independent of shear stresses.
- The results of a series of tests on CO_2 foams identified reductions in chemical costs derived from the synergistic effects of co-surfactant systems using a good foaming agent and a less-expensive but poor foaming agent. The required good foaming agent was reduced by at least 75%. Additionally, the deleterious effect on injectivity was reduced by as much as 50% using the co-surfactant system, compared with a previously used surfactant system.
- The order (highest to lowest) of calcium lignosulfonate (CLS) adsorption onto five powdered pure minerals common to oil reservoirs is montmorillonite > kaolinite > dolomite > calcite > silica. In each case, adsorption is complete within 1 hour. Core samples of sandstone, limestone, and dolomite took an order of magnitude longer to equilibrate. This difference appears to be related to the pore structure.

Benefits/Impacts

CO_2 mobility control will result in more-efficient CO_2 flooding in heterogeneous reservoirs and will include the following benefits:

- Extending the life of the petroleum reservoir, increasing oil recovery, and expanding the range of reservoirs amenable to CO_2 flooding.
- Reducing chemical costs by optimizing oil saturation tolerance of foam, decreasing primary foaming agent adsorption, and decreasing primary foaming agent concentration.
- Delaying production of CO_2 and increasing retention of CO_2 in the reservoir (sequestration).
- Improving injectivity of CO_2 and water and decreasing mobility of CO_2 during the alternate injection of brine and CO_2.



Relative adsorption of two surfactants CD 1045™ (a good foamer) and a calcium lignosulfonate (a sacrificial agent) onto five minerals.

PROJECT facts

U.S. Department of Energy
Office of Fossil Energy
National Energy Technology Laboratory

Application of Time-Lapse Seismic Monitoring for the Control and Optimization of CO_2 Enhanced Oil Recovery Operations

DE-FC26-04NT15425

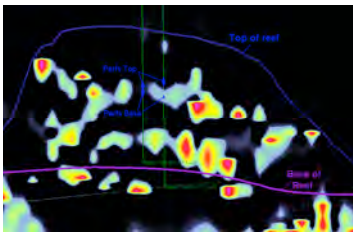
PARTNERS

Schlumberger Data & Consulting Services
Pittsburgh, PA

New Horizon Energy
Traverse City, MI

MAIN SITE

Pittsburgh, PA



Relative adsorption density of two surfactants onto five minerals.

Background/Problem

During the 1970s and 1980s, a number of Silurian Reef oilfields were discovered on the northern and southern flanks of the Michigan Basin. These fields have produced over 1 billion barrels of oil to date and are in the late stage of their primary productive life. Enhanced oil recovery (EOR) projects in these fields using CO_2 injection guided by 4-D seismic monitoring will ensure that the maximum remaining reserves are recovered. This technology also will apply to monitoring CO_2 sequestration projects in the future.

Description

This project is being conducted in two phases. The objective of the first phase is to characterize a selected carbonate reef reservoir in the Michigan Basin using advanced evaluation methods to assess the potential of a CO_2 flood. This reservoir characterization includes advanced petrophysical, geophysical, geological, reservoir engineering, and reservoir simulation technologies. The objective of the second phase is to demonstrate the benefits of using advanced seismic methods for monitoring the CO_2 flood fronts.

The project has established a mappable correlation between low instantaneous frequency and high porosity. This relationship has been supported by a wavenumber study conducted with the depthed volume. The relationship will be tested when an existing borehole is sidetracked into a high-porosity volume predicted with this technique. Should this relationship be proved, it will allow the porosity distribution through these reefs to be mapped accurately. Reservoir simulations needed to optimize the field's CO_2 injection parameters then can incorporate seismically detected porosity volumes to predict CO_2 migration in carbonates.

Phase I of the project has been completed. The reservoir has been characterized, and reservoir simulation techniques used to match the production history have been developed. Injection of small amounts of CO_2 has begun.

Instantaneous frequency expected to map porosity distribution

Accomplishments

Researchers selected a Silurian-age reef in the Northern Reef trend of the Michigan Basin for a CO_2 flood. Existing geological information was used to develop a rock property volume that then was used to model and optimize the seismic acquisition parameters.

A base 3 seismic survey was acquired over the Silurian reef. The research team performed basic seismic processing on the acquired 3-D data and interpreted the data volume. Seismic-attribute analysis was performed, and a potential relationship was noted between lower instantaneous frequency and porosity over 5%.

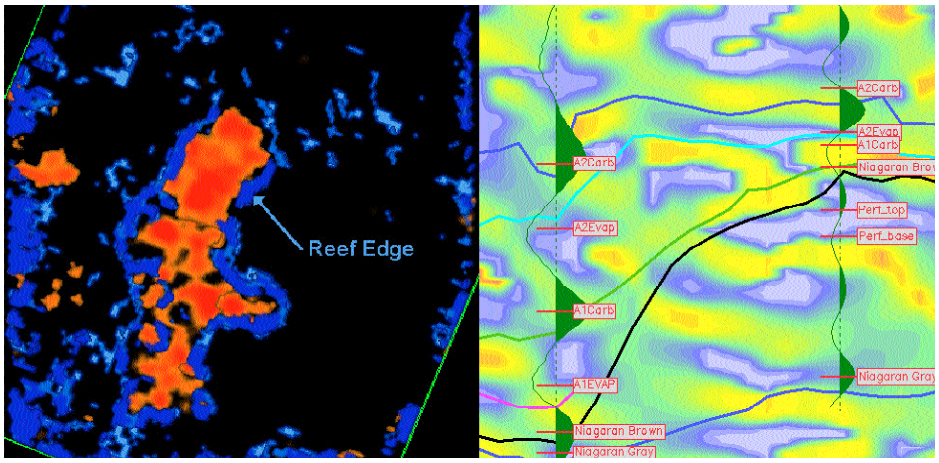
Project researchers, using the initial porosity volume, conducted a preliminary reservoir simulation and production history matching. A number of existing wellbores in the reef were worked over in preparation for the commencement of CO_2 injection operations. Small volumes of CO_2 were injected in the upper section of the northern end of the reef.

Researchers completed azimuthal processing on the 3-D seismic data and performed an azimuthal velocity analysis on this data set. A depth volume also was generated and interpreted.

Benefits/Impacts

If it is confirmed that instantaneous frequency can be used to accurately predict the distribution of >5% porosity throughout these reefs, this will allow for highly accurate reservoir simulations and greater reserve recoveries, thereby resulting in the most optimized EOR projects possible. Monitoring of CO_2 floods will result in the ability to modify the injection parameters to recover more oil and sequester more CO_2.

CO_2 flooding potential has been demonstrated in the United States, particularly in the Permian Basin of west Texas and southeast New Mexico. Much of the research on CO_2 flooding methods can be applied to other gas flooding processes, such as hydrocarbon injection projects. Today over 300,000 b/d of oil is being produced by gas injection in the United States, and that volume scarcely hints at the potential of a remaining untapped oil resource pegged at 351 billion barrels.



(left) Composite Blended Seismic Attribute display. This display combines high amplitude and high variance for two time slices (855 and 860 msec.) and clearly shows the reef's edge. (right) Instantaneous Frequency Display. Shown are two synthetic seismograms for two wells (on and off reef) used for well-to-seismic ties overlain on an Instantaneous Frequency slice through the reef. Note the low-frequency zone (blue) corresponding to the perforated (high-porosity) interval.

CONTACT POINTS

Roy Long
Technology Manager
U.S. DOE
918-699-2017
roy.long@netl.doe.gov

Virginia Weyland
Project Manager
U.S. DOE
918-699-2041
virginia.weyland@netl.doe.gov

Brian Toelle
Principal Investigator
Schlumberger Technology Corporation
412-787-5403
toelle1@slb.com

TOTAL ESTIMATED COST

$9.0 million

COST SHARING

DOE	$2.0 million
Non-DOE	$7.0 million

PROJECT START/END

Start	March 1, 2004
End	February 28, 2008

WEBSITE

www.netl.doe.gov

PROJECT facts

U.S. Department of Energy
Office of Fossil Energy
National Energy Technology Laboratory

Investigation of Efficiency Improvement During CO_2 Injection in Hydraulically and Naturally Fractured Reservoirs

DE-FC26-01BC15361

PARTNER

Texas Engineering Experiment Station (TEES)
Texas A&M University
College Station, TX

MAIN SITE

Texas A&M University
College Station, TX

Background/Problem

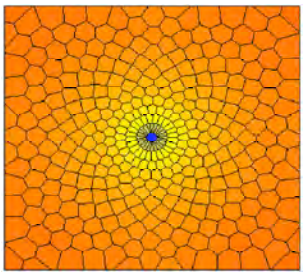
As more technical knowledge accumulates, it becomes clear that natural and hydraulically induced fractures often dominate reservoir sweep efficiency and therefore impact the economics of CO_2 floods. The brittle nature of low-permeability reservoirs, which are amenable to CO_2 flooding, make them prone to natural and induced fractures.

The fundamental mechanisms of CO_2 movement through fracture systems are virtually unexplored. The goal of the proposed work was to advance the understanding of this dynamic process and determine the implications on the ultimate performance of bypassing reserves during CO_2 injection.

Description

The project objective was to perform unique laboratory experiments with artificially fractured cores (AFCs) and X-ray computer tomography (CT) to examine the physical mechanisms of bypassing in hydraulically and naturally fractured reservoirs that eventually result in lower recovery rates from CO_2 flooding in heterogeneous or fracture-dominated reservoirs.

This project used an X-ray CT scanner to image saturation profiles of flow patterns for direct measurement of bypassing mechanisms and to measure bypassed oil to optimize CO_2 flooding efficiency. With this equipment, researchers have established the relationship between fracture aperture distribution and overburden pressures. They found that CO_2 gravity drainage still plays an important role in oil recovery, even in a short-matrix block. CO_2 sweep efficiency was improved significantly by controlling the CO_2 mobility in the fracture with viscosified water and placing a cross-linked gel in the fracture. As of February 2006, all the project tasks have been completed, and the final report is being prepared.



Pressure distribution map with unique gridding technique.

Improved CO_2 mobility control in fractured reservoirs

CONTACT POINTS

Roy Long
Technology Manager
U.S. DOE
918-699-2017
roy.long@netl.doe.gov

Daniel Ferguson
Project Manager
U.S. DOE
918-699-2047
daniel.ferguson@netl.doe.gov

David Schechter
Principal Investigator
Texas A&M
937-845-2275
schech@spindletop.tamu.edu

TOTAL ESTIMATED COST

$1.1 million

COST SHARING

DOE	$0.9 million
Non-DOE	$0.2 million

PROJECT START/END

Start	September 28, 2001
End	December 31, 2005

WEBSITE

www.netl.doe.gov

Accomplishments

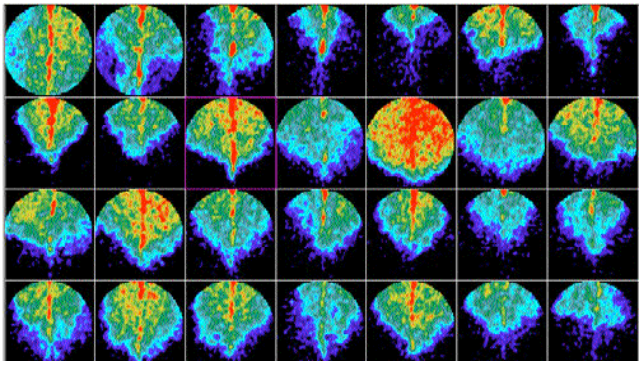
Project highlights include the following:

- New laboratory experiments have been developed to 1) demonstrate the effect of different overburden pressures and injection rates on fracture aperture and matrix and fracture productivities, and 2) mitigate bypassing mechanisms that will result in less bypassing and more-efficient CO_2 flooding in fracture-dominated reservoirs.
- Tests that varied CO_2 injection rates and WAG (water-alternating-gas) injection ratios were conducted at the laboratory scale. Fluid flow experiments where a gel polymer was placed in the fracture system were also performed.
- The laboratory techniques have been used to reduce CO_2 bypassing and optimize CO_2 flood design in the Wasson Field of west Texas.
- Analytical and numerical modeling has been performed to 1) investigate the effect of fracture aperture at variable overburden pressure, 2) study the effect of different rock heterogeneity on flow path contributors, 3) validate the use of cubic law equation, 4) examine the transfer mechanism during core flooding in fractured cores, and 5) assess the effect of grid orientation in different mobility ratios.
- A new discrete fracture simulator with flexible and unstructured gridding techniques was developed to accurately model the fluid flow through fracture networks with multiple orientations.

Benefits/Impacts

In the United States, oil that is potentially producible by advanced recovery methods amounts to 200 billion barrels. Of the available advanced oil recovery methods, gas injection has the greatest potential for additional oil recovery from domestic light oil reservoirs. CO_2 flooding is the most promising gas injection technique for widespread use among enhanced oil recovery (EOR) technologies.

While a number of CO_2 projects are underway in the United States, there are many reservoirs that are not being considered for CO_2 flooding or any type of EOR methods because of extreme heterogeneity or natural fractures. The results of this work are expected to improve the effectiveness of CO_2 recovery and make the recovery process attractive for a wide range of reservoirs.



X-ray images of a CO_2 front movement through a fractured core, showing the influence of gravity segregation.

PROJECT facts

U.S. Department of Energy
Office of Fossil Energy
National Energy Technology Laboratory

Improvement of Sweep Efficiency in Gas Flooding

DE-FC26-04NT15535

PARTNER

University of Houston
Houston, TX

MAIN SITE

Houston, TX

Background/Problem

Miscible and near-miscible gas flooding has proven to be one of the few cost-effective enhanced oil recovery techniques in the past 20 years. The sweep efficiency of such processes often is not high because of the adverse viscosity ratio and density difference between the solvent gas and the oil as well as the reservoir heterogeneity. Water-alternating-gas (WAG) processes often are used to improve sweep efficiency. Foams and direct thickeners have been developed but not used routinely in the field. The effect of new well architectures on sweep efficiency is poorly understood. As the scope of miscible flooding is being expanded to medium-viscosity oils in shallow sands in Alaska and shallower reservoirs in the Lower 48, there are questions about sweep efficiency in near-miscible regions. This project is aimed at evaluating the sweep efficiency of various miscible flood processes at the laboratory scale.

Description

The goal of this work is to evaluate the sweep efficiency of various miscible flooding processes in a laboratory model, develop numerical tools to estimate sweep efficiency at the field scale, and identify the solvent composition, mobility control method, and well architecture that improve sweep efficiency.

A high-pressure quarter 5-spot cell has been constructed to conduct multicontact miscible WAG displacements at reservoir conditions. Multicontact miscible solvents are identified by conducting slimtube experiments for a medium viscosity oil (78 cp). Coreflood experiments are conducted to determine microscopic displacement efficiency as a function of WAG ratio. Quarter 5-spot experiments are conducted to infer sweep efficiency in a 3-D geometry at the laboratory scale. A compositional model has been developed to simulate such displacements in the laboratory and in the field.

This project is in its second year. As of January 2006 researchers have completed four subtasks: slimtube tests, high-pressure model construction, corefloods, and 1-D compositional modeling. Three-dimensional modeling of the sweep efficiency of gas/WAG floods is in progress. Use of other oil/solvent systems and foams and field-scale modeling will be conducted in 2007.

Laboratory-scale CO_2 studies improve recovery

CONTACT POINTS

Roy Long
Technology Manager
U.S. DOE
918-699-2017
roy.long@netl.doe.gov

Jim Barnes
Project Manager
U.S. DOE
918-699-2076
jim.barnes@netl.doe.gov

Kishore K. Mohanty
Principal Investigator
University of Houston
713-743-4331
mohanty@uh.edu

TOTAL ESTIMATED COST

$0.8 million

COST SHARING

DOE	$0.6 million
Non-DOE	$0.2 million

PROJECT START/END

Start	September 20, 2004
End	September 30, 2007

WEBSITE

www.netl.doe.gov

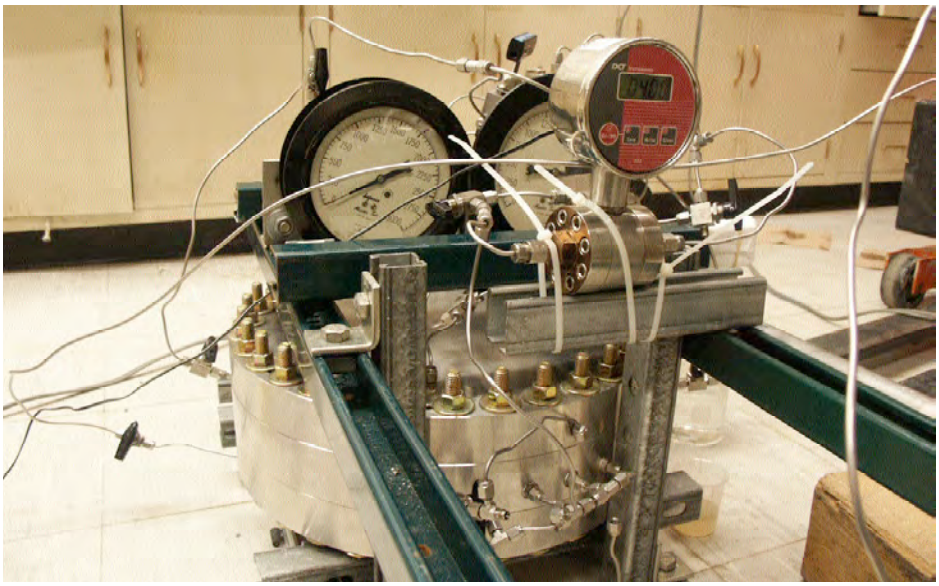
Accomplishments

The following observations have been made from the work performed:

- Ethane is a multi-contact miscible solvent for one of the oils tested at pressures higher than 1,340 psi. WAG improves the microscopic displacement efficiency (~100%) over continuous gas injection followed by waterflood (~67%) in corefloods.
- WAG improves oil recovery (~75%) in the quarter 5-spot over continuous gas injection followed by waterflood (~64%). WAG injection slows down gas breakthrough. A decrease in the slug size improves the oil recovery in WAG floods. Use of a horizontal production well lowers oil recovery vs. a vertical production well during continuous gas injection.
- The sweep efficiency has not been measured directly in the quarter 5-spot cell, but it is expected that as the recovery increases so does the sweep efficiency. These experiments will be matched by compositional simulations to infer the sweep efficiency of these processes.

Benefits/Impacts

The experimental data on sweep efficiency will help evaluate multicontact miscible flooding processes at the laboratory scale. Reservoir simulators should be tuned to such experiments before being used for field-scale process optimization. The methodology developed in this project would help improve miscible oil recovery projects. CO_2 flooding methods can be applied to other gas flooding processes, such as hydrocarbon injection projects.



Front view of the quarter 5-spot high-pressure cell.

PROJECT facts

U.S. Department of Energy
Office of Fossil Energy
National Energy Technology Laboratory

Field Demonstration of Carbon Dioxide Miscible Flooding in the Lansing-Kansas City Formation, Central Kansas

DE-FC26-00BC15124

PARTNERS

University of Kansas
Kansas Geological Survey
Tertiary Oil Recovery Project
Lawrence, KS

Murfin Drilling Company and working interest partners
Wichita, KS

U.S. Energy Partners, LLC
Russell, KS

EPCO Carbon Dioxide Products, Inc.
Monroe, LA

MAIN SITE

Hall-Gurney Field
Russell County, KS

Carter Colliver #1 CO_2 injection well is shown in the background and the Colliver #13 producing well in the foreground, both part of the first CO_2 flood in Kansas.

Background/Problem

This CO_2 miscible flood demonstration project represents the first use of CO_2 for enhanced oil recovery (EOR) in Kansas. The goal is to demonstrate the technical feasibility of the process in a major Kansas reservoir. The Hall-Gurney field, the largest Lansing-Kansas City formation oilfield in Kansas, is one of several CO_2 flood candidate fields in central Kansas. There have been no miscible CO_2 floods in Kansas, primarily due to the distance to CO_2 sources.

This electricity co-generation, ethanol fuel production, and CO_2 EOR project is a unique, scalable model for linked energy systems. Waste heat from a 15-megawatt, gas-fired turbine municipal electrical generator provides heat input for a 25 million gallon per year ethanol plant. CO_2 is obtained as a byproduct from ethanol production and is being utilized by the CO_2 miscible flood project in Hall-Gurney field. The full CO_2 stream from the ethanol plant could supply a small oilfield capable of producing 5 million barrels of oil and sequestering 1.5 million tons of CO_2 over a 20 year period.

Description

Initial studies of the Lansing-Kansas City carbonate reservoir have determined the technical and economic feasibility of using CO_2 miscible flooding to recover residual and bypassed oil in central Kansas. The demonstration is the first time that CO_2 from an ethanol plant has been used for EOR. The project offers potential to add significant value to waste CO_2 through EOR. The CO_2 from the ethanol plant was being vented into the atmosphere before the start of this project.

CO_2 flooding began in December 2003. The CO_2 is trucked 7 miles from the ethanol plant in Russell, KS, and injected into the depleted Lansing-Kansas City reservoir. If the technology is economically feasible and applied to other Kansas fields, the estimated incremental oil production in the state of Kansas is 100-600 million barrels over 20 years.

The pilot covers half of a traditional 5-spot pattern on 10 acres with one central injector, three producers, and two water injection containment wells. CO_2 breakthrough and the first incremental oil production began in May 2004.

EOR pilot uses waste CO_2 from an ethanol plant

CONTACT POINTS

Roy Long
Technology Manager
U.S. DOE
918-699-2017
roy.long@netl.doe.gov

Paul West
Project Manager
U.S. DOE
918-699-2035
paul.west@netl.doe.gov

Paul Willhite
Co-Principal Investigator
University of Kansas
Tertiary Oil Recovery Project
785-864-2906
willhite@ku.edu

TOTAL ESTIMATED COST

$5.4 million

COST SHARING

DOE	$1.9 million
Non-DOE	$3.5 million

PROJECT START/END

Start	March 8, 2000
End	March 7, 2010

WEBSITE

www.netl.doe.gov

By the end of June 2005, about 16.92 million pounds of CO_2 had been injected. The average rate of CO_2 injection for the previous six months was about 245,000 cubic feet per day. The initial production was 100% water, with oil arriving in February 2004. Oil rates averaged 3.8 barrels per day during January–June 2005. Incremental oil production was 1,494 barrels. Since then, neither production well has experienced increased daily oil production rates expected with the arrival of the oil bank. The volume of CO_2 produced has remained low, with gas/oil ratios on the order of 4,000-5,000. The amount of gas produced was 4.97 million standard cubic feet, which is about 3.4% of the injected CO_2. Injection was converted to water on June 21, 2005, in an effort to reduce operating costs to a breakeven level, with the expectation that sufficient CO_2 has been injected to displace the oil bank to the production wells by water injection.

Benefits/Impacts

CO_2 flooding demonstrated in this project may prevent up to 6,000 mature oilfields in Kansas from being abandoned. The potential target for CO_2 flooding in Kansas may total over 250-500 million barrels of incremental oil, equivalent to 5-10 years of additional Kansas production. The project's original objective, to demonstrate to Kansas independents the feasibility of CO_2 flooding and to find a viable supply of CO_2, is being met by joint industry ventures. This will benefit agriculture, ethanol production, and electrical generation in addition to independent oil producers. At the same time the public will gain the environmental benefit of less CO_2 in the atmosphere.

The electrical co-generation, ethanol production, and EOR project is unique in that it brings together three distinctly separate industries in a way that improves the economics of each while also providing a mechanism for value-added geologic sequestration of CO_2. If the full CO_2 stream from the ethanol plant is utilized for EOR for a 10-year period, the benefits from the three industry linkages would total $88 million.

Currently, the CO_2 project uses only 10% of the CO_2 produced from the ethanol plant. Hall-Gurney field could use the full CO_2 output of five similar-sized ethanol plants at full-field CO_2 EOR development.

Hall-Gurney field and nearby ethanol plant, Russell, KS.

PROJECT facts

U.S. Department of Energy
Office of Fossil Energy
National Energy Technology Laboratory

4-D High-Resolution Seismic Reflection Monitoring of Miscible CO_2 Injection into a Carbonate Reservoir

DE-FC26-03NT15414

PARTNER

University of Kansas
Center for Research
Lawrence, KS

MAIN SITE

Hall-Gurney field
Russell County, KS

Data acquisition in most areas around the site has been consistent throughout the almost two years of recording. Photo courtesy of Kansas Geological Survey.

Background/Problem

Time-lapse 3-D (or 4-D) seismic reflection surveying has been proven an effective tool during the last decade to evaluate the effectiveness of conventional EOR programs. Consistency and repeatability of 3-D surveys has been the most frequently identified problem associated with time-lapse monitoring of reservoir production. Seismic monitoring has been considered viable only for the most prolific fields, possessing the greatest potential for significant returns from identification of stranded reserves. Most U.S. Midcontinent reservoirs would not be considered candidates for 4-D monitoring using historical criteria.

Only recently has the potential of seismically monitoring the injection of miscible CO_2 into thin carbonate reservoirs been studied. Field tests of this technique to date have used conventional approaches with minimal regard to the economics of routine application or to the spatial and temporal sampling necessary for application to the size of most reservoirs found in the Midcontinent. Changes in reservoir characteristics between baseline and monitoring surveys have assumed linearity and have not been incorporated into improved production schemes. This project follows on the DOE CO_2 flood project being conducted at Hall-Gurney field to evaluate the feasibility of CO_2 flooding in central Kansas.

Description

This project is designed to address questions related to both EOR flood management and CO_2 sequestration in mature, shallow, and thin carbonate reservoirs. Important aspects related to flood management include delineating preferential CO_2 pathways, enhancing sweep efficiency, locating areas of bypassed oil, and defining the mechanisms controlling CO_2 movement.

As a secondary component, assessing the feasibility of this methodology for applications in CO_2 sequestration includes identifying preferential pathways for CO_2 movement, delineating features that might influence long-term containment of CO_2, detecting movement of CO_2 outside containment at a high enough resolution to provide the necessary public assurances, and defining the minimum survey requirements for effective long-term monitoring.

Efficiency of EOR programs relies heavily on accurate reservoir models. Movement of miscible CO_2 injected into a thin (~5 meters), shallow-shelf, oomoldic carbonate reservoir around 900 meters deep in Russell County, KS, is being monitored successfully with high-resolution 4-D time-lapse seismic techniques. High-resolution seismic methods show great potential for incorporation into CO_2 flood management, thus highlighting the

Seismic data a potential tool for routine CO_2 sequestration

CONTACT POINTS

Roy Long
Technology Manager
U.S. DOE
918-699-2017
roy.long@netl.doe.gov

Paul West
Project Manager
U.S. DOE
918-699-2035
paul.west@netl.doe.gov

Rick Miller
Principal Investigator
Kansas Geological Survey
785-864-2091
rmiller@kgs.ukans.edu

TOTAL ESTIMATED COST

$2.9 million

COST SHARING

DOE	$2.3 million
Non-DOE	$0.6 million

PROJECT START/END

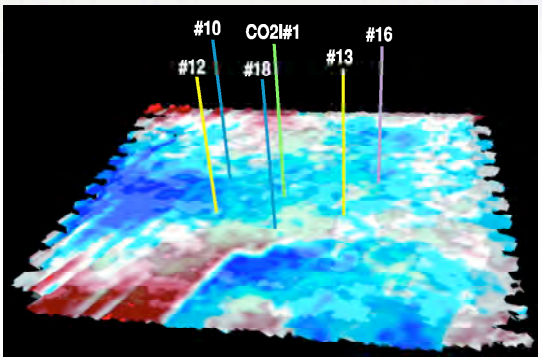
Start	September 8, 2003
End	August 31, 2009

WEBSITE

www.netl.doe.gov

necessity of frequently updated reservoir-simulation models, especially for carbonates. Use of an unconventional approach to acquisition and interpretation of the high-resolution time-lapse/4-D seismic data was key to the success of this monitoring project.

Twelve 3-D seismic reflection surveys will be conducted over 6 years to develop and refine appropriate methodologies for monitoring the injection and containment of miscible CO_2 in a thin carbonate reservoir in central Kansas.



Horizon map overlay of similarity-facies attribute and time structure map.

Accomplishments

Differences interpreted on consecutive time-lapse seismic horizon slices are consistent with CO_2 injection volumetrics, match physical restraints based on engineering data and model amplitude response, and honor production data. Textural characteristics in amplitude envelope images appearing to correspond to non-uniform expansion of the CO_2 through the reservoir honors both the lineaments identified on baseline data and changes in containment pressures. Interpretations of a set of time-lapse seismic images can be correlated to a mid-flood alteration of the injection/production scheme intended to improve containment and retard excessive northward movement of the CO_2.

The injection of CO_2 was halted, and water injection began as part of a water-alternating-gas scheme in July 2005. At that time, seven 3-D surveys had been completed (six monitor and one baseline) within about 18 months. The first monitor survey after water injection was scheduled for January 2006. Based on flood simulations, water injection should severely alter the pressure and fluid distribution across the entire field within six months. Results from the January 2006 survey should provide uniquely different images of the reservoir relative to the last year of CO_2 injection.

Benefits/Impacts

Continued success seismically monitoring CO_2 movement through this reservoir will reveal critical components and considerations necessary for routine incorporation of 3-D high-resolution seismic monitoring with CO_2 enhanced oil recovery (EOR) programs in thin, relatively shallow, mature carbonate reservoirs.

Changes in production schemes made possible by incorporating nearly real-time monitoring data into CO_2 injection EOR programs could dramatically improve the efficiency and economics of that technology in many Midcontinent fields. Refinements to 3-D high-resolution reflection-imaging approaches resulting from this study could make seismic data a tool for providing assurances essential for routine sequestration of CO_2 in depleted oil/gas fields.

PROJECT facts

U.S. Department of Energy
Office of Fossil Energy
National Energy Technology Laboratory

Evaluation and Enhancement of Carbon Dioxide Flooding Through Sweep Improvement

DE-FC26-04NT15536

PARTNER

University of Oklahoma
Norman, OK

MAIN SITE

University of Oklahoma
Norman, OK

Background/Problem

Carbon dioxide ($CO_{2)}$ displacement is a common improved recovery method applied to light oil reservoirs. The economic and technical success of CO_2 floods is often limited by poor sweep efficiency or large CO_2 utilization rates.

This project is studying the effectiveness of CO_2 flooding in a mature reservoir to identify and develop methods and strategies to improve oil recovery in CO_2 floods. The objective of the project is to develop a methodology for improving sweep efficiency and reducing CO_2 utilization rates by performing a detailed post-mortem on a mature CO_2 project in Little Creek field in Mississippi.

Description

The purpose of this project is to evaluate CO_2 displacement efficiency in a mature oil reservoir. Little Creek field is being studied to relate laboratory displacement results and simulated performance predictions to the historical reservoir performance to determine sweep efficiency, improve understanding of the reservoir response to CO_2 injection, and develop scaling methodologies to relate laboratory data and simulation results to predicted reservoir behavior. The field provides actual reservoir performance with which to compare the predicted performance.

The study of Little Creek field will identify strategies to improve recovery from the reservoir through understanding conformance control and sweep in the current operations. Based on the knowledge gained during this study, methods will be developed for predicting conformance control and sweep efficiency that can be extended to other CO_2 injection projects, in progress or planned, and ultimately yield improved oil recoveries due to CO_2 flooding and reduce CO_2 utilization rates.

Slim-tube miscibility-testing equipment.

Project post-mortem to yield technology improvements

CONTACT POINTS

Roy Long
Technology Manager
U.S. DOE
918-699-2017
roy.long@netl.doe.gov

Chandra Nautiyal
Project Manager
U.S. DOE
918-699-2021
chandra.nautiyal@netl.doe.gov

Michael Wiggins
Principal Investigator
University of Oklahoma
405-325-6781
mwiggins@ou.edu

TOTAL ESTIMATED COST

$1.0 million

COST SHARING

DOE	$0.7 million
Non-DOE	$0.3 million

PROJECT START/END

Start	September 1, 2003
End	August 30, 2009

WEBSITE

www.netl.doe.gov

Accomplishments

An historical evaluation of sweep efficiency in the Little Creek CO_2 flood is being conducted. Performance predictions from reservoir simulations are being compared with actual historical performance data, including displacement studies, conformance issues, and sweep efficiency. Laboratory displacement studies are being conducted to correlate actual reservoir performance to simulation and laboratory studies for CO_2 flooding.

A simulation exercise is underway to match historical reservoir performance prior to the initiation of the CO_2 flood in order to develop a dynamic reservoir model for use in predicting performance based on actual reservoir conditions.

The reservoir model developed will be extended to reservoirs that may be CO_2 flooding candidates. Laboratory studies of CO_2 displacement of heavy oils will be conducted to improve the confidence of recovery estimates made for this application. The studies are expected to yield an improved understanding of the feasibility of CO_2 flooding heavy oil reservoirs, obstacles that need to be overcome, and potential solutions to those obstacles.

Benefits/Impacts

Martin and Taber (1992) have estimated that an incremental 5-30 billion barrels of oil could be recovered from CO_2 flooding in the United States, depending on the oil price and economic incentives. Taber, et al. (1997) projected that about 80% of the world's reservoirs could recover some incremental oil from CO_2 flooding. With this much potential for economic benefit, the question becomes: Why have more CO_2 floods not been initiated? The answer is primarily the cost of the CO_2. Floods that are near CO_2 infrastructure are recovering significant amounts of incremental oil, while those that are a distance from the infrastructure are debating the economics of extending pipelines and compression facilities to outlying areas. Minimizing the utilization rate through intelligent application of mobility and conformance-control measures would greatly improve the economics of extending the infrastructure to these outlying areas by ensuring that the CO_2 contacts more of the reservoir. Knowledge gained from this detailed analysis will yield improved operating practices that will serve as a guide to improving oil recovery in active CO_2 floods and as a strategy for implementing new CO_2 floods.

CO_2 separation facilities at Little Creek field.

PROJECT facts

U.S. Department of Energy
Office of Fossil Energy
National Energy Technology Laboratory

Synthesis and Evaluation of CO_2 Thickeners

DE-FC26-04NT15533

PARTNER

University of Pittsburgh
Pittsburgh, PA

MAIN SITE

University of Pittsburgh
Pittsburgh, PA

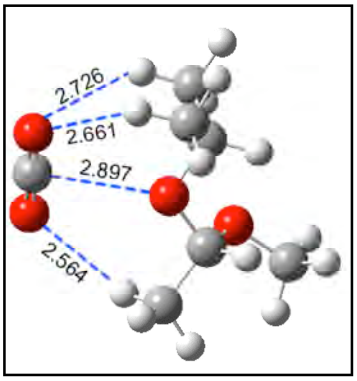
Background/Problem

The University of Pittsburgh research group, under previous funding from DOE, designed, synthesized, and evaluated the first CO_2 thickener, poly(fluoroacrylate-styrene), or polyFAST, in the laboratory. PolyFAST remains the only CO_2 thickener that has ever been reported (DE-FC26-01BC15315).

Although this project proved that a thickening agent could be designed for CO_2, it was not a practical thickener for field application. Specifically, PolyFAST was expensive, biologically and environmentally persistent, and not available in large volumes. All of these negative attributes were directly the result of the polymer having a high content of fluorine.

A second project, also funded by DOE, researched inexpensive polymers that could dissolve in carbon dioxide and increase its viscosity, thereby improving mobility control of CO_2 floods. The project evaluated numerous polymers that contained no fluorine for this CO_2 thickening application. Specific chemical groups that were known to have a strong and favorable interaction with CO_2 were selected for study. The research identified the most CO_2-soluble, high-molecular-weight, commodity polymer that has yet been reported: poly(vinyl acetate), or PVAc. Unfortunately, the pressure required to dissolve PVAc in CO_2 was much greater than the range of the pressures used in most CO_2 floods.

Description



CO_2 (left) interacting with a monomer of PAO (right).

The objective of this research is to use molecular modeling techniques, coupled with the researchers' prior experimental results, to design, synthesize, and evaluate inexpensive, non-fluorous CO_2 thickening agents. The first type of thickener to be considered is associating polymers.

Molecular modeling is being used to design polymers that are more CO_2-soluble than PVAc, will dissolve below the minimum miscibility pressure (MMP), and will generate a two- to ten-fold decrease in CO_2 mobility at concentrations of 0.01–1.0 percent by weight. Although most of the thickeners envisioned are copolymers, researchers also are evaluating several small hydrogen-bonding agents and surfactants with oligomeric (very short polymer) tails that form viscosity-enhancing structures in solution.

Three steps are required to accomplish the project goals. First, a highly CO_2-philic, hydrocarbon-based monomer must be identified. Polymers or oligomers (small polymers) of this monomer must exhibit high CO_2 solubility at EOR MMP conditions. Second, the molecular weight of a homopolymer of the CO_2-phile must be increased as much as possible without causing the polymer to become insoluble in CO_2. Finally, a small concentration of a CO_2-phobic moiety that promotes viscosity-enhancing macromolecular interactions while not substantially diminishing CO_2 solubility must be incorporated into the polymer.

CONTACT POINTS

Roy Long
Technology Manager
U.S. DOE
918-699-2017
roy.long@netl.doe.gov

Betty Felber
Project Manager
U.S. DOE
918-699-2031
betty.felber@netl.doe.gov

Robert Enick
Principal Investigator
University of Pittsburgh
412-624-9649
rme@pitt.edu

TOTAL ESTIMATED COST

$1.0 million

COST SHARING

DOE	$0.8 million
Non-DOE	$0.2 million

PROJECT START/END

Start	September 10, 2004
End	August 31, 2007

WEBSITE

www.netl.doe.gov

Design based on molecular modeling

Researchers at Yale University are assisting the University of Pittsburgh team in the design and synthesis of novel monomers. Yale will be solely responsible for the synthesis of a second type of thickener: small, hydrogen-bonding compounds. These molecules have a core that contains one or more hydrogen-bonding groups, such as urea or amide groups. Non-fluorous, CO_2-philic functional groups will be attached to the hydrogen-bonding core of the compound to impart CO_2 stability and macromolecular stability to the linear "stack" of these compounds.

Accomplishments

The research group has successfully designed the first CO_2-soluble ionic surfactants that are highly soluble in CO_2. The most promising surfactant has a structure similar to the widely used commercially surfactant Aerosol OT, but the hydrocarbon tails have been replaced with oligomers (short polymers) of PVAc.

Most of the team's work has focused on the use of chemical groups with carbon, hydrogen, and oxygen, such as the acetate group, to enhance CO_2 solubility. Researchers also have found that tert-butyl groups, which are composed solely of carbon and hydrogen, also impart CO_2 solubility to compounds. They have established this trend for small, non-polar compounds and ionic surfactants and hope to determine whether the t-butyl group can increase the CO_2 solubility of polymeric compounds. The inclusion of the simple t-butyl group into compounds may be an inexpensive and easy way to induce CO_2 solubility.

The project has resulted in the:

- Successful use of *ab initio* calculations to design polymers. Researchers identified two monomer groups that exhibit stronger interactions with CO_2 than with vinyl acetate.
- Synthesis of poly(3-acetoxy oxetane), or PAO, and polymethoxy methyl ether, or PMME. Project performers were able to synthesize and characterize low-molecular-weight versions of both PAO and PMME and expect to test their CO_2 solubility soon.
- Synthesis of CO_2-soluble ionic surfactants. Researchers synthesized the first non-fluorous CO_2-soluble ionic surfactant by using short PVAc "tails" and are to test its ability to reduce mobility soon.

Benefits/Impacts

About 1.5 billion standard cubic feet of CO_2 is injected in domestic oil reservoirs every day in dozens of CO_2 flooding projects that produce roughly 200,000 barrels of oil per day, yet CO_2 flood performance still has room for improvement because of the low viscosity of dense CO_2. For example, about 8,000 standard cubic feet of CO_2 injection is required for each barrel of oil recovered. Further, large slugs of water must be injected alternately with slugs of CO_2 (WAG) in an attempt to suppress CO_2 "fingering." This project is expected to identify an inexpensive CO_2 thickener composed primarily of carbon, hydrogen, and oxygen that delays breakthrough of CO_2, reduces the amount of CO_2 required to recover a barrel of oil, and doubles or triples the oil production rate.

National Energy
Technology Laboratory

626 Cochrans Mill Rd.
P.O. Box 10940
Pittsburgh, PA 15236-0940

3610 Collins Ferry Rd.
P.O. Box 880
Morgantown, WV 26507-0880

One West Third St., Suite 1400
Tulsa, OK 74103-3519

2175 University Avenue South, Suite 201
Fairbanks, AK 99709-4910

1450 Queen Avenue SW
Albany, OR 97321-2198

Roy Long
Technology Manager, E&P
918-699-2017
roy.long@netl.doe.gov

Visit the NETL website at:
www.netl.doe.gov

Customer Service:
1-800-553-7681

U.S. Department of Energy
Office of Fossil Energy

March 2006