Sequestration of CO_2 in a Depleted Oil Reservoir: An Overview

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Abstract

Geologic sequestration of CO_2 in depleted oil reservoirs, while a complex issue, is thought to be a safe and effective carbon management strategy. This paper provides an overview of a NETL-sponsored R&D project to predict and monitor the migration and ultimate fate of CO_2 after being injected into a depleted oil reservoir as part of a micropilot scale field experiment. The Queen Formation sandstone, located in the West Pearl Queen field in SE NM, was identified as the CO_2 injection site for this project. Core samples of this formation were obtained for lithologic analysis and laboratory experimentation. Preliminary flow simulations were run using this data and suggest that at least 2000 tons of CO_2 can be injected into the reservoir over a period of one month. Our planned suite of computer simulations, laboratory tests, field measurements and monitoring efforts will be used to calibrate, modify and validate the modeling and simulation tools. Ultimately, the models and data will be used to predict storage capacity and physical and chemical changes in oil reservoir properties. Science or technology gaps related to engineering aspects of geologic sequestration of CO_2 also will be identified in this study.

Introduction

Carbon dioxide sequestration in geologic formations is the most direct carbon management strategy for long-term removal of CO_2 from the atmosphere, and is likely to be needed for continuation of the US fossil fuel-based economy and high standard of living. Subsurface injection of CO_2 into depleted oil reservoirs is a carbon sequestration strategy that might prove to be both cost effective and environmentally safe. Part of this confidence is due to an extensive knowledge base about site-specific reservoir properties and subsurface gas-fluid-rock processes from the mining and petroleum industries, including those from recent EOR CO_2 flooding activities (Morris, 1996). However, CO_2 sequestration in oil reservoirs is a complex issue spanning a wide range of scientific, technological, economic, safety, and regulatory concerns, requiring more focused R&D efforts to better understand its cost and consequences (DOE Offices of Science and Fossil Energy report, 1999).

Objective

Our project, "Sequestration of CO_2 in a Depleted Oil Reservoir: A Comprehensive Modeling & Site Monitoring Project," is funded by the DOE/NETL Carbon Sequestration program. One of the program's stated goals is to provide the science and technology basis to properly evaluate the safety and efficacy of long-term CO_2 sequestration in geologic formations. The specific objective of our project is to better understand CO_2 sequestration processes in a depleted oil reservoir. Because of the nature of an oil reservoir and the presence of multiple phases, CO_2 sequestration mechanisms can include hydrodynamic trapping, aqueous solubility or mineralization. Viscous fingering, gravity separation, miscible fluids, reaction kinetics, and possible leakage through fractures are but a few of the processes that also can affect geologic sequestration effectiveness. Broad project goals include computer simulations and laboratory measurements of fluid flow and reaction, as well as a field experiment in order to better understand the complex nature of geosequestration processes. The micropilot field experiment calls for injection of several thousand tons of CO_2 into a depleted oil reservoir. An ideal site for this project would be located in a geologically simple setting in porous and permeable sandstone, having a recent development and production history, and where no secondary water or enhanced CO_2 treatments have been used. These site parameters allow for simplified modeling and easier interpretations of field results. Specific R&D objectives for this project include:

- Characterization of oil reservoir and its capacity to sequester CO_2
- Prediction of multiphase fluid migration & interactions
- Development of improved remote (geophysical) monitoring techniques
- Measurement of CO_2-reservoir reactions

Approach

The West Pearl Queen field, which is owned and operated by Strata Production Company of Roswell, NM, was chosen as our field demonstration site to study geologic sequestration of CO_2. This field is located near Hobbs, New Mexico and was first developed in 1984, producing about 250,000 barrels of oil. Production has slowed in recent years as the reservoir pressure in some wells fell below levels required for profitable oil recovery. This field has not been subjected to secondary or enhanced oil recovery operations with water or CO_2. The main producing zone for this field is the Queen Formation, which is a small structural dome of arkosic sandstone about 25 feet in thickness (Figure 1). The Pearl Queen field seems to be an ideal site to study CO_2 migration and interactions after injection into a depleted oil reservoir. Injection is planned for Stivason-Federal #4 well, while other wells (Stivason-Federal #1, 3 & 5) will be used for remote monitoring.

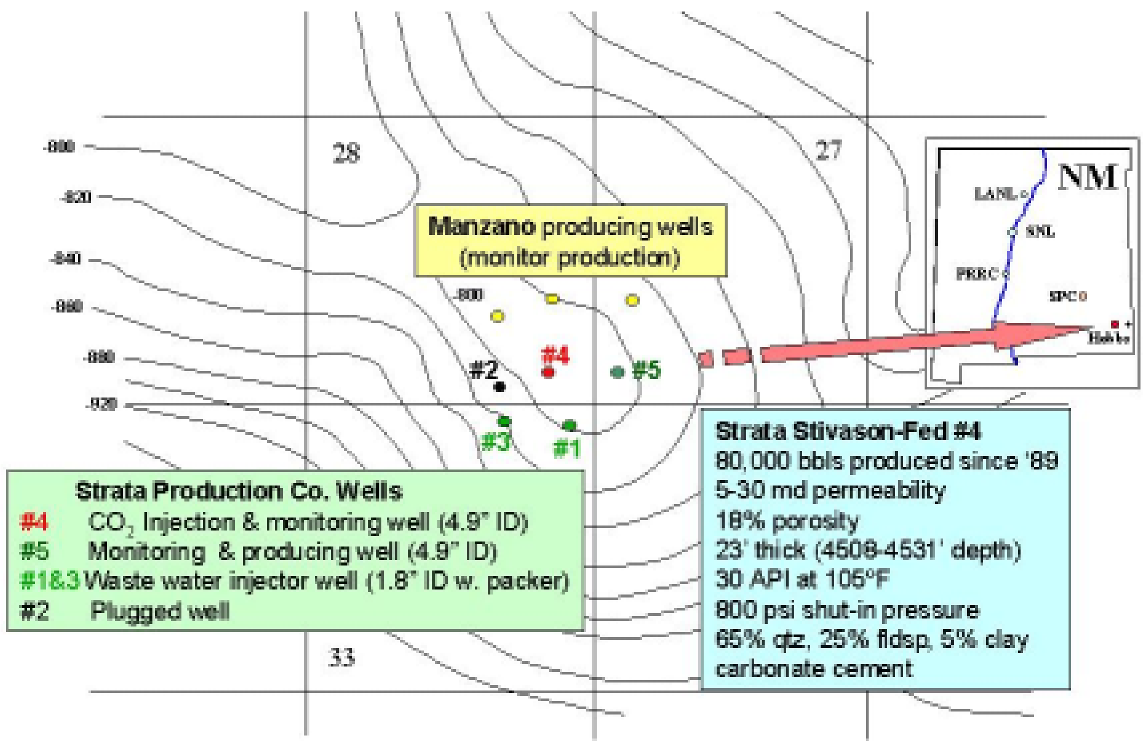

Figure 1. Location of the West Pearl Queen Field, and Structure map for top of Queen F. (20' contour interval; datum S. L.)

This project utilizes a suite of computer simulations, laboratory tests, field measurements and monitoring efforts to understand those physical and chemical processes governing geologic sequestration of CO_2 in oil reservoirs. The micropilot demonstration calls for injection of several thousand tons of CO_2 into the Queen Formation, followed by a comprehensive suite of geophysical field surveys to monitor the advance of the CO_2 plume and lab experiments to measure geochemical changes in reservoir mineralogy and permeability. Specific field and lab observations will be used to calibrate, modify and validate the modeling and simulation tools. The field demonstration, however, will be the ultimate test of our computer simulations.

Project Description

This field demonstration project has three phases: I) baseline characterization, II) CO_2 injection and soaking, and III) post-injection characterization. Phase I includes compilation of a geologic model for the depleted reservoir, evaluation of available flow and reaction simulators, well preparation, acquisition of legal permits, collection of reservoir fluids, and baseline geophysical surveys of the reservoir. Phase II of this project involves the design of the micropilot field test, preparation of surface injection facilities, refinement of computer simulation models, injection of 2000-4000 tons of CO_2 over a one month period, measurement of fluid pressure changes or plume breakthroughs and geophysical surveys of the plume. Phase III of the project includes wellhead venting of the injected CO_2, and downhole pumping of residual fluids and final geophysical surveys. Our project combines geologic, flow and reaction path modeling and simulations, injection of CO_2 into the oil-producing formation, geophysical monitoring of the advancing CO_2 plume and laboratory experiments to measure reservoir changes with CO_2 flooding. The field data will provide a unique opportunity to test, refine and calibrate the computer model(s) that will simulate those subsurface interactions. Iteration of modeling, laboratory and field data is crucial to the improvement of simulation tool methodologies.

<u>Modeling and Simulation</u>

Our ability to accurately predict the migration and fate of CO_2 in oil reservoirs is limited by inadequate reservoir characterization as well as the lack of a comprehensive simulator to model coupled chemical, hydrological, mechanical and thermal (CHMT) processes. However, existing commercial and research codes, such as ECLIPSE and FLOTRAN, are available and will be used to simulate some of the important geoprocesses involved during CO_2 sequestration (e.g., three-phase flow and geochemical reactions). The goal of this task is to choose one or more codes that have the ability to simulate the coupled processes that occur during injection and migration of CO_2 in the depleted oil reservoir. These codes will be evaluated based on availability, cost, ease of use, robustness and flexibility to modification. With the selected code(s) and input data from a geologic model, a computer model will be built for a depleted oil reservoir, which will incorporate site-specific information and previous characterization results. This model will be used to aid in designing a micropilot field study of high-flow CO_2 injected in the depleted oil reservoir. The geologic model will integrate available data on stratigraphy and reservoir rock properties, including wireline logs, structure-contour and isopach maps, core samples from the Stivason-Federal well #1, and appropriate regional geologic data.

Geophysical Monitoring

State of the art geophysical techniques are one of the few ways to remotely characterize oil reservoir properties and changes due to injection of CO_2. Remote geophysical sensing techniques will be used prior to, during and after CO_2 injection, consisting of borehole geophysics, surface to borehole surveys, and surface reflection seismic surveys. These surveys will identify and characterize formation changes due to saturation and injection effects (Knight et. al., 1998; Withers and Batzle, 1997). The borehole geophysics will include dipole sonic logs, limited microseismic surveys during injection and multi-level, 3C crosswell seismic surveys. The surface to borehole seismic surveys will include a Vertical Seismic Profile (VSP) in which receivers are placed in the injection wellbore to detect arrivals from surface shots (e.g., Lizarralde and Swift, 1999). The 4D, 9C seismic surveys will be run before and after injection, as well as a third survey conducted after flow-back of the injected CO_2.

Field Demonstration

Our micropilot demonstration calls for injection of several thousand tons of CO_2 into the Queen Formation at a depth of about 4500 feet using the Stivason-Federal well #4 as the injection well. This reservoir is geologically simple and consists of a small structural dome of thinly bedded sandstones. Although the reservoir is pressure depleted (<3.0 MPa), it has not been subjected to secondary oil recovery treatment with water or CO_2, and is therefore an ideal site to study the effects of CO_2 injection in a depleted oil reservoir. Strata Production Company will coordinate all field preparations, surveys and injection operations.

Laboratory Tests

Mineralization is the geochemical interaction of CO_2 with sedimentary minerals to form stable and environmentally benign carbonate phases, and is a desired sequestration end stage. However, the nature and kinetics of CO_2-dominated fluid/mineral interactions is not well understood. This knowledge is essential for the prediction of carbonation reactions and the formation of carbonate minerals that will be responsible for the long-term confinement of CO_2 into the reservoir. Our project will examine static and non-static flow experiments of pure CO_2 and CO_2-H_2O mixtures interacting with plugs of Queen Formation sandstone for time periods up to 15 months at reservoir conditions (P=4.5 MPa, T=40°C). Static tests will explore the effects of fluid chemistry and flow on mineral dissolution and precipitation reactions. Non-static flow (percolation) tests will elucidate the effects of fluid-mineral interaction on rock porosity and permeability. Solid and liquid samples from these tests will be analyzed for chemical, structural and morphological changes using standard geochemical techniques. These results should provide critical information on the mechanisms and rates of CO_2-mineral interactions in a depleted oil reservoir.

Results

Geology

Approximately 30 ft of discontinuous, four-inch diameter core of the Queen Formation (Shattuck Sandstone Member) from the Stivason Federal #1 well was available for study and to develop a geologic model. This well is approximately 1200' from our injection well and its core should be representative of the reservoir. No natural fractures are present in this core, although it is not precluded for the rest of the reservoir. In general, the Shattuck Sandstone consists of irregularly bedded sandstones, siltstones, and sandy siltstones, containing irregular anhydrite beds and nodules. The sandstones are a heterogeneous mix of oxidized detrital sands and siltstones, with detrital and authigenic cements of dolomite, gypsum, anhydrite, and halite. The main reservoir lithology (lithology C in Figure 2) is a poorly cemented, oil stained sandstone exhibiting between 15-20% porosity and irregular permeabilities up to 200 millidarcies (Figure 2). The percentage of the reservoir represented by this lithology is unknown due to missing core, although about a third of the core available consists of this facies. The upper parts of the core represent the confining strata rather than the reservoir rock. The likely reservoir sandstone represents about

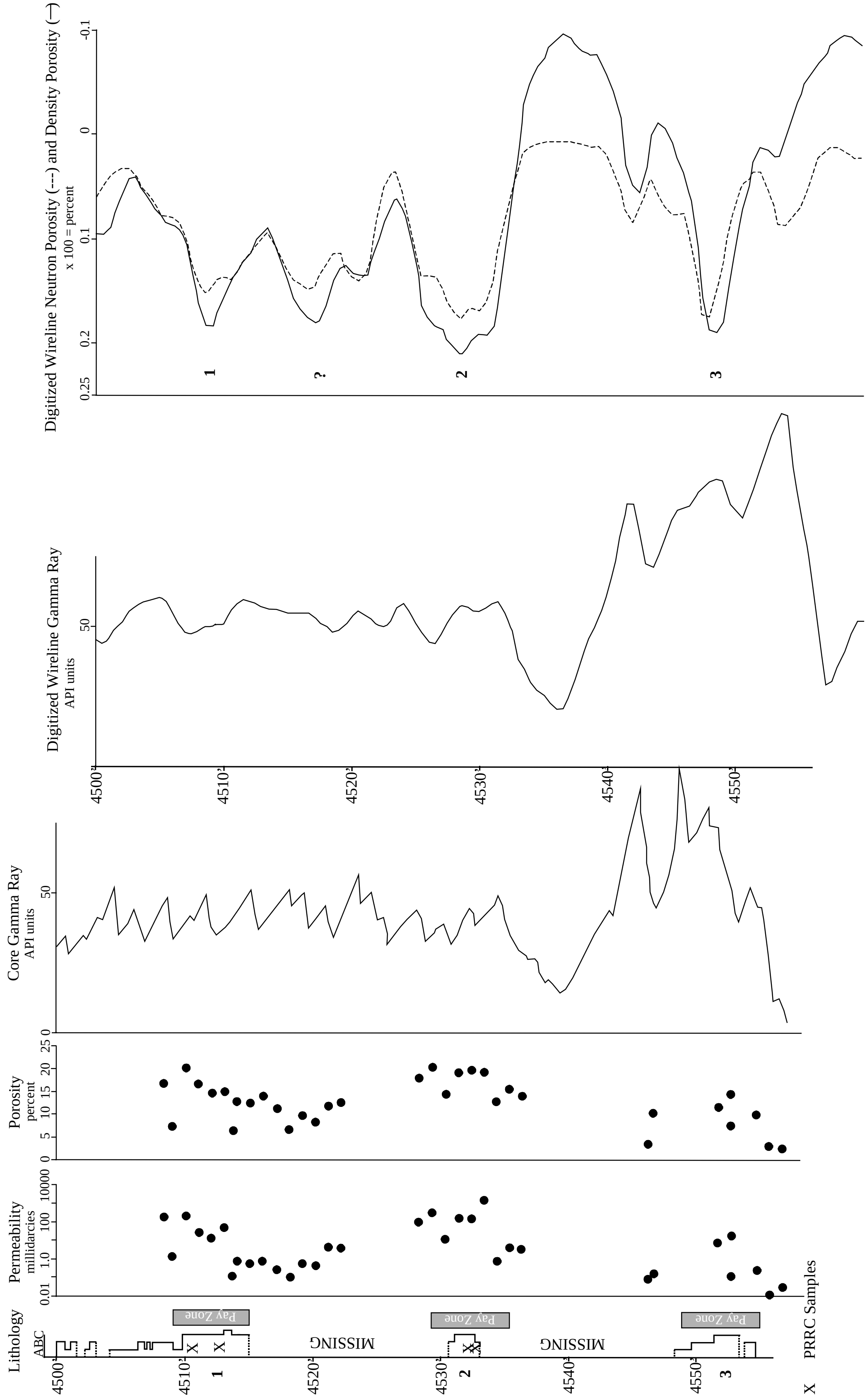

Figure 2. Chart showing the lithologic and geophysical properties of the Stivason Federal well #1 core with depth, and correlated to permeability, porosity and gamma ray logs; shaded intervals are oil stained and are likely sequestration zones.

80% of the core available from the designated main reservoir intervals. Oil staining suggests high porosities and that they will be the primary hosts for injected CO_2 as long as local hydrofracture pressure is not exceeded during injection. The variability in oil staining and measured permeability shown by this lithology suggests that some of the residual oil may be difficult to displace during CO_2 injection.

Non-reservoir strata contain more pore-lining illite and chlorite, as well as illite/smectite and anhydrite cements (Mazzullo, et al., 1991). Mineralogic changes caused by CO_2 injection into these heterogeneous strata would probably occur in the cementing mineral phases, most likely in the carbonates and sulfates. The heterogeneity of the cements suggests that a thorough base-line characterization prior to injection would be necessary in order to fully understand and document any changes caused by injection.

Flow Modeling

Porous media flow simulations were used to match the historic production data. Values of a number of unknown reservoir rock and fluid properties had to be determined by trial and error due to lack of appropriate data. The reservoir model was subsequently used to determine feasibility of injecting CO_2 over a period of one month. A number of injection scenarios were tested to determine the response of the reservoir over a wide range of operating conditions and regulatory operational constraints. The preliminary injection studies indicate that the injected CO_2 plume can be dispersed in the Shattuck Formation sandstones to such an extent that it can be characterized through a variety of proposed monitoring techniques. More details of the geologic and flow modeling can be found in Pawar, et al. (2001).

Pearl Queen Brine Chemistry

Brine samples taken from wells Stivason Federal #4 and Stivason Federal #5 (see Figure 1) were analyzed for cations and anions using Direct Current Plasma (DCP) spectroscopy and ion chromatography (IC); pH was measured using a pH electrode. The chemical analyses (Table 1) show that these oil-field brines are mainly composed of Na and Cl with an ionic strength of ~2.4 Molar. There is a charge imbalance of about 0.3 Molar (due to an excess of negative charges), and the Al concentrations in the brines are suspiciously high, perhaps due to the presence of colloids. Additional chemical analyses should resolve these concerns, and will allow for subsequent calculation of equilibrium mineral phases. We suspect that the Pearl Queen brine is close to equilibrium with gibbsite, kaolinite, dolomite, calcite and quartz. Total carbon analyses are scheduled soon. Preliminary reaction path modeling of CO_2 mixing with the brine shows an initial sharp decrease in pH as expected. Preliminary modeling of low pH fluid interactions with the estimated major modal mineralogy of the Shattuck Member sandstone (75% quartz, 10%-15% K-feldspar, and 5%-10% dolomite cement), and for several modal fractions of initial dolomite, shows the resulting fluid pH ranges from 4-5 after reaction with these minerals. This preliminary result is an indication of the potential buffering capacity of the reservoir when the low pH CO_2-brine reacts with the Queen Formation during injection. Further modeling trials are needed when considering different CO_2 fugacities and initial mineral fractions.

Table 1. Chemical analyses of brines from Stivason Federal wells # 4 and #5[1]

Well #	pH	Al[2]	Si	Na	K	Mg	Ca	Cl	Br	SO_4
#5	6.786	0.000414	0.00014533	2.085	0.00268	0.123	0.056	2.99	0.0041	0.0208
#5	6.852	0.000410	0.00013823	2.044	0.00307	0.122	0.056	3.12	0.0040	0.0220
#4	7.181	-	-	1.797	0.00264	0.110	0.049	-	-	-

[1] Analyses performed at the NMBMMR, Socorro, NM on same samples yielded similar results.

[2] Elemental compositions reported as molarity (moles/L)

Geophysical Monitoring

Negotiations are underway to schedule pre-injection geophysical surveys, including dipole sonic logs, a deviation survey and a 3 component crosswell survey. We are planning to have the 3C Vertical Seismic Profile survey and the 3D, 9C surface seismic surveys completed by the end of FY01, immediately prior to CO_2 injection.

Application

Ultimately, the models and data resulting from this CO_2 sequestration project will be used to predict geologic storage capacity and physical and chemical changes in reservoir properties, such as fluid composition, porosity, permeability and phase relations. Development of accurate monitoring tools will also permit validation of the computer simulations that will be needed for future performance and risk assessments. Science or technology gaps related to engineering aspects of CO_2 sequestration will be identified in the course of this study. In addition, a better understanding of CO_2-reservoir interactions resulting from this project should improve industrial EOR flooding practices.

Future Activities

Current geologic and preliminary flow simulation results indicate the feasibility of CO_2 injection in a depleted oil reservoir. These results also provide guidelines for upcoming geophysical monitoring (e.g., spacing of seismic sources and receivers). Geochemical lab experiments with Shattuck Member sandstones have been initiated to evaluate mineralization reaction kinetics. Preparation for CO_2 injection and acquisition of geophysical surveys has begun and should be completed by the end of FY01. CO_2 injection is scheduled for the beginning of FY02. Final characterization and modeling efforts will be completed in FY03. Upon completion of this project, the West Pearl Queen reservoir will be one of the most completely characterized oil reservoirs, setting the stage for follow-on DOE/NETL CO_2 sequestration experiments. This field site could be used for field demonstration experiments of greater scope and duration, including injection of larger volumes of CO_2, soaking of CO_2 for a duration significantly longer than a month, drilling of additional observation wells or sampling of the reservoir for actual core analysis.

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