THE GEO-SEQ PROJECT: FIRST-YEAR STATUS REPORT

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ABSTRACT

The GEO-SEQ Project is a public-private applied R&D partnership, formed with the goal of developing the technology and information needed to enable safe and cost-effective geologic sequestration by the year 2015. The effort, supported by the U.S. Department of Energy s (DOE s) National Energy Technology Laboratory, involves Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, Oak Ridge National Laboratory, Stanford University, the U.S. Geological Survey, the Texas Bureau of Economic Geology, the Alberta Research Council, and five private-sector partners Chevron, Texaco, BP, Pan Canadian Resources, and Statoil. The partnership conducts applied research and development focused on three broad goals: (1) reducing the cost of sequestration, (2) decreasing the risk of sequestration, and (3) decreasing the time to implementation. To achieve these goals, nine individual subtasks are currently underway. These subtasks include: development of methods to co-optimize EOR and sequestration; development of carbon-sequestration-enhanced gas production from natural gas reservoirs; evaluation of the effects of SO_X and NO_X on geochemical reactions between CO_2, water, and reservoir rocks; identification of geophysical techniques for monitoring CO_2 migration in the subsurface; field testing of geophysical-monitoring techniques; development of tracer techniques for monitoring the interaction between CO_2, water and reservoir rocks; a reservoir simulation-code comparison study for predicting the fate of CO_2 in the subsurface; enhancement of simulation models for carbon- sequestration-enhanced coal-bed methane recovery; and improved capacity assessment for brine formations. The purpose of this paper is to present an overview of the early progress on these activities and, more importantly, to evaluate progress in the context of the overall goals of the GEO-SEQ project.

INTRODUCTION

The purpose of the GEO-SEQ project is to establish a public-private R&D partnership that will:

- **Lower the cost of geologic sequestration** by (1) developing innovative optimization methods for sequestration technologies, with collateral economic benefits such as enhanced oil recovery (EOR), enhanced gas recovery (EGR), and enhanced coalbed methane production, and (2) understanding and optimizing trade-offs between CO_2 separation and capture costs, compression and transportation costs, and geologic-sequestration alternatives.

- **Lower the risk of geologic sequestration** by (1) providing the information needed to select sites for safe and effective sequestration, (2) increasing confidence in the effectiveness and safety of sequestration by identifying and demonstrating cost-effective monitoring technologies, and (3) improving performance-assessment methods to predict and verify that long-term sequestration practices are safe and effective and do not introduce any unintended environmental impact.
- **Decrease the time to implementation** by (1) pursuing early opportunities for pilot tests with our private sector partners and (2) gaining public acceptance.

All of these activities will take place with the participation, advice, and cooperation of the U.S. Department of Energy s National Energy Technology Laboratory (NETL) and our industry partners, thereby assuring the practicality of our approaches and resulting in rapid technology transfer. To ensure broad stakeholder input and wide dissemination of the results of this project, we have an advisory council with membership that reaches beyond the immediate partners. In addition, we will (at timely intervals) prepare and disseminate educational and informational materials to inform the public about geologic sequestration. Interaction and engagement of the international community of researchers and government entities that are pursuing R&D in geologic sequestration are also critical to the success of this project.

PROJECT TEAM

The GEO-SEQ Project includes a core team of scientists and engineers from a number of organizations, including:

- Three of DOE s national laboratories   Lawrence Berkeley National Laboratory (LBNL), Lawrence Livermore National Laboratory (LLNL), and Oak Ridge National Laboratory (ORNL)
- Stanford University
- Texas Bureau of Economic Geology (TBEG)
- U.S. Geological Survey (USGS)
- Alberta Research Council (ARC)
- Five industry partners   Chevron, Texaco, Pan Canadian Resources, BP-Amoco, and Statoil.

In addition, through ongoing collaborations and our advisory committee, our team extends to include other universities and a number of public and private research organizations.

APPLIED R&D PLAN

The GEO-SEQ project team is carrying out the four coordinated and interrelated applied R&D tasks listed in Table 1. The specific R&D tasks were selected to meet the overall goals of the project and identified as high priority needs in the extensive sequestration roadmapping exercise sponsored by the Department of Energy (Reichle et al., 2000) and summarized in Benson (2000). In addition to the R&D tasks listed in Table 1, GEO-SEQ will also carry out public outreach, which includes workshop sponsorship and participation, active engagement of our advisory council, a middle-school education program, undergraduate and graduate research opportunities, and a GEO-SEQ Web page that keeps our partners and the public informed about geologic sequestration and the progress of the project.

The publications and abstracts prepared by the GEO-SEQ team to date are listed at the end of this paper. In addition, more information about the GEO-SEQ Project can be found at http://www-esd.lbl.gov/GEOSEQ/.

Table 1. Applied R&D tasks for the GEO-SEQ Project.

Task	**Subtask**	**Investigators**
Task A. Develop sequestration co-optimization methods for EOR, depleted gas reservoirs, and brine formations.	A-1. Co-optimization of carbon sequestration and EOR and EGR from oil reservoirs.	Franklin Orr and Anthony Kovscek, Stanford University
	A-2. Feasibility assessment of carbon sequestration with enhanced gas recovery in depleted gas reservoirs.	Curt Oldenburg and Sally Benson, LBNL Tony Kovscek, Stanford University
	A-3. Evaluation of the impact of CO_2, aqueous fluid, and reservoir rock interactions on the geologic sequestration of CO_2, with special emphasis on the cost implications.	Kevin Knauss and Carl Steefel, LLNL Karsten Pruess and Chin Fu Tsang, LBNL
	A-4. Life-cycle cost analysis for sequestration in brine formations.	Katherine Yuracko, ORNL
Task B. Evaluate and demonstrate *monitoring technologies* for verification, optimization, and safety.	B-1. Sensitivity modeling and optimization of geophysical monitoring technologies.	Larry Myer, Mike Hoversten, Don Vasco, Ernie Majer, LBNL Robin Newmark, LLNL
	B-2. Field data acquisition for CO_2 monitoring using geophysical methods.	Ernie Majer and Mike Hoversten, LBNL Robin Newmark, LLNL
	B-3. Application of natural and introduced tracers for optimizing value-added sequestration technologies.	David Cole and Jerry Moline, ORNL
Task C. Enhance and compare *computer simulation models* for predicting, assessing, and optimizing geologic sequestration in brine, oil and gas, and coalbed-methane formations.	C-1. Enhancement of numerical simulators for greenhouse gas sequestration in deep, unminable coal seams.	Bill Gunter and David Law, ARC Karsten Pruess, LBNL Bert van der Meer, TNO Franklin Orr and Anthony Kovscek, Stanford University
	C-2. Intercomparison of models for simulating sequestration in geologic formations.	Karsten Pruess and Chin Fu Tsang, LBNL Kevin Knauss and Carl Steefel, LLNL
Task D. Improve the methodology and information available for *capacit*y assessment of sequestration sites.	Evaluate sequestration capacity for a range of hypothetical and actual brine, oil, and gas formations.	Susan Hovorka, P. Knox and T. Trembley, TBEG Sally Benson and Karsten Pruess, LBNL Roger Aines, LLNL Collaborators: Robert Burruss, USGS

STATUS REPORT

Co-optimization of Carbon Sequestration and Enhanced Oil Recovery (EOR) and Enhanced Gas Recovery (EGR) from Oil Reservoirs

The objectives of this effort are (1) to assess the feasibility of co-optimization of CO_2 sequestration and EOR and (2) to develop techniques for selecting the optimum gas composition for injection. Results will lay the groundwork necessary for rapidly evaluating the performance of candidate sequestration sites as well as monitoring the performance of CO_2 EOR. To date, existing CO_2—EOR selection criteria have been examined in light of the need to maximize CO_2 storage in a reservoir. Criteria tables (see Table 2) considering reservoir engineering and surface facilities as part of combined EOR and sequestration were developed.

Table 2. Screening criteria for anthropogenic CO_2-EOR and CO_2 sequestration.

	Positive Indicators	**Cautionary Indicators**
Reservoir Properties		
$S_o\phi$	≥ 0.05	< 0.05 Consider filling reservoir voidage if capacity is large
kh	$\geq 10^{-14}$ - 10^{-13}	$< 10^{-14}$ If kh is less, consider whether injectivity will be sufficient
Capacity (kg/m^3)	> 10	< 10
Seals	Adequate characterization of caprock, minimal formation damage	Areas prone to fault slippage
Oil Properties		
ρ (°API, kg/m^3)	> 22, 900	< 22 Consider immiscible CO_2 EOR, fill reservoir voidage if C is large
μ (mPa s)	< 10	> 10 Consider immiscible CO_2 EOR
Composition	High concentration of C_5 to C_{12}, relatively few aromatics	n/a
Surface Facilities		
Corrosion	CO_2 can be separated to 90% purity; development of epoxy coated pipe and corrosion inhibitors	H_2O and H_2S concentration above 500 ppm each
Pipelines	Anthropogenic CO_2 source is within 500 km of a CO_2 pipeline or oil field	Source to sink distance is greater than 500 km
Synergy	Preexisting oil production and surface facilities expertise	Little or no expertise in CO_2-EOR within a geographic region

Carbon Sequestration Enhanced Gas Recovery (CSEGR)

The objectives of this effort are to assess the feasibility of injecting CO_2 into depleted natural gas reservoirs to simultaneously sequester carbon and enhance methane (CH_4) recovery. Investigations include assessments of (1) CO_2 and CH_4 flow and transport processes, (2) injection strategies that retard mixing, (3) novel approaches to inhibit mixing, and (4) identification of candidate sites for pilot study.

Injection of CO_2 into depleted gas reservoirs has the potential to sequester significant quantities of CO_2 (140 GtC worldwide, IEA 1997) while simultaneously enhancing CH_4 recovery. Many aspects of this approach for sequestration are favorable, including: (1) the carbon density for CO_2 is nearly twice that of CH_4 at typical reservoir pressures and temperatures; (2) the mobility ratio for CO_2 displacement of CH_4 is favorable, thereby limiting viscous fingering; (3) the greater density of CO_2 compared to CH_4 will lead to gravity segregation, thereby limiting mixing; and (4) revenues from the enhanced gas recovery can be used to offset the cost of sequestration. Nevertheless, valid concerns about degrading the quality of the produced gas with CO_2 have limited the development of this concept. A few studies have investigated the feasibility of CSEGR, with mixed conclusions regarding the efficacy of this approach. More importantly these studies have shown that the conclusions are highly dependent on the specific assumptions about the nature of the reservoir.

To provide a greater insight into the conditions under which CSEGR is feasible, reservoir simulations have been performed using the TOUGH2 model with an equation of state for water-CO_2-CH_4 mixtures (Oldenburg et al., 2001). These simulations have been based on a conceptual model of the Rio Vista Gas Field, the largest on-shore dry-gas field in California. Reservoir simulations that assume a homogenous (but anisotropic) reservoir indicated more than 5 years of enhanced methane recovery was possible before CO_2 breakthrough occurred. To obtain more realistic assessment of CO_2 breakthrough, simulations have recently been performed using stochastically generated permeability fields, one of which is shown in Figure 1. CO_2 transparent over a ten-year period in this reservoir is shown in Figure 2. These simulations confirm that permeability heterogeneities can lead to early breakthrough, but nevertheless, for the wide range of conditions examined, significant CH_4 recovery could be achieved before breakthrough occurs.

Figure 1. Heterogeneous permeability field used for simulations of CSEGR.

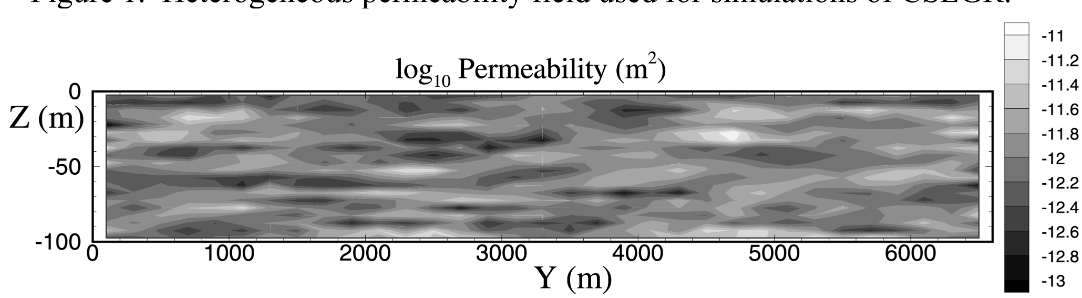
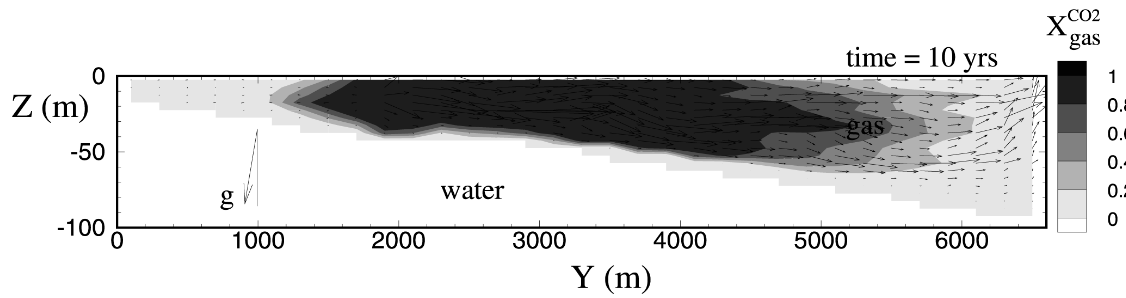


Figure 2. Distribution of CO_2 in a natural gas reservoir after ten years of injection.



Evaluation of the Impact of CO_2 Aqueous Fluid and Reservoir Rock Interactions on the Geologic Sequestration of CO_2, with Special Emphasis on Economic Implications

Lowering the costs of the front-end processes can dramatically lower the overall costs of sequestration. One approach is to sequester less-pure CO_2 waste streams that are less expensive or require less energy to separate from flue gas. The objective of this research is to evaluate the impact of this impure CO_2 waste stream on geologic sequestration.

To date, the influence of SO_2, NO_2, and H_2S on CO_2/rock/water interactions has been evaluated to determine dissolution/precipitation reactions and consequent changes in formation mineralogy and formation porosity. Initially, the specific impact of SO_2 very near the well bore in a feldspathic-sandstone reservoir was investigated. Now we have expanded these studies by looking at the specific impact of adding (separately) NO_2 and then H_2S to the CO_2 waste stream, while broadening the scope to include an idealized carbonate reservoir. Simulations equivalent to batch-type (closed-system) reactions have been performed, including full-dissolution kinetics (that in turn included acid catalysis) for all of the mineral phases present in the reservoir rock. Rock composition and modal abundances appropriate for a feldspathic-sandstone reservoir were used (for a reservoir containing clay and carbonate with and without a Fe-bearing phase, and a carbonate reservoir comprised of calcite, dolomite, and siderite).

Having performed these early simulations, it is now important to begin working with researchers who are trying to find more cost-effective separation techniques. Together, optimized solutions for lowering the overall cost of sequestration should be possible.

Sensitivity Studies for Evaluating Geophysical Monitoring Techniques

The objectives of this effort are to (1) demonstrate methodologies for and carry out an assessment of the effectiveness of candidate geophysical monitoring techniques, (2) provide and demonstrate a methodology for designing an optimum monitoring system, and (3) provide and demonstrate methodologies for interpreting geophysical and reservoir data, to obtain high-resolution reservoir images. Four different methods for monitoring CO_2 migration are currently being evaluated, alone and in combination, to determine which monitoring approaches have the spatial resolution and sensitivity needed to monitor CO_2 sequestration (namely, crosswell seismic imaging, crosswell electromagnetic imaging, electrical resistance tomography (ERT), and gravity). Software tools that combine the output of reservoir simulators with forward and inverse geophysical models have been used to evaluate the effectiveness of seismic, electromagnetic, and gravitational techniques for detecting CO_2 migration at the Lost Hills, California, CO_2 EOR pilot (Hoversten and Myer, 2000; Myer, 2000). The possibility of using ERT as a cost-effective monitoring method is being evaluated for a CO_2 EOR project in Kansas (Ramirez et al., 2000).

Field Trials of High Resolution Geophysical Monitoring Methods

The goal of this effort is to demonstrate, through field testing, the applicability of single-well seismic, crosswell seismic, surface-to-borehole seismic, crosswell electromagnetic (EM), and electrical-resistance tomography (ERT) methods for subsurface imaging of CO_2. Progress to date includes obtaining baseline measurements of the pre-CO_2 injection surveys at the Lost Hills EOR pilot being conducted by Chevron. Post-injection surveys will be obtained during the spring and summer of 2001.

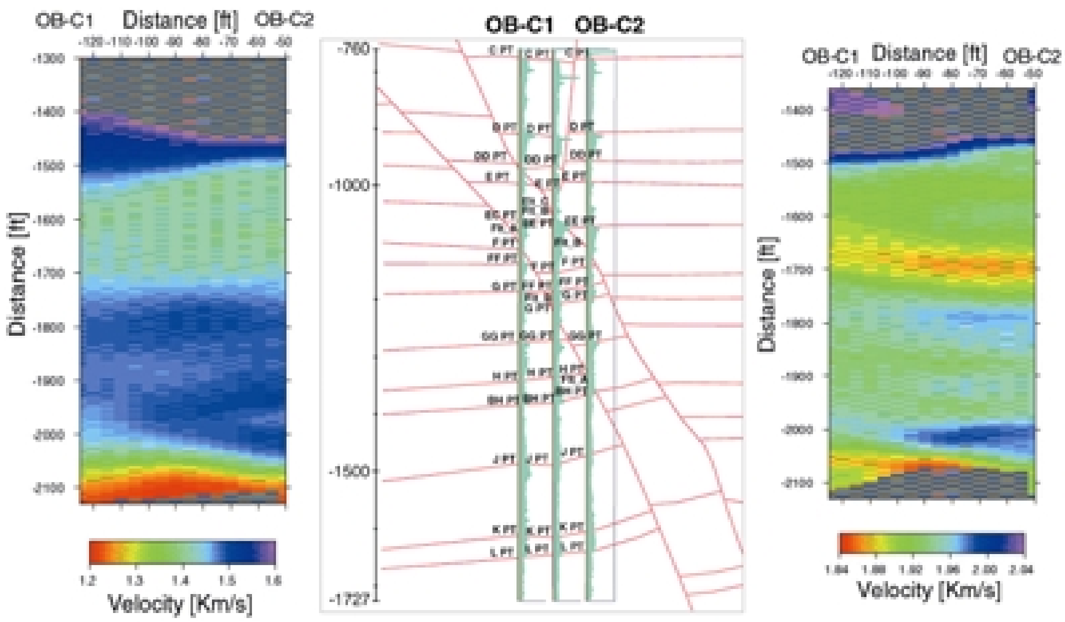
The Lost Hills Oil Field occurs in a diatomite formation, a formation with extremely high porosity but low permeability and rock strength. The pilot project consists of injecting CO_2 into a five-spot pattern on 1.5-acre spacing and provides an excellent opportunity for evaluating the effectiveness of a variety geophysical monitoring techniques. However, the complexities of the diatomite reservoir (and many other reservoirs) make direct measurement of one property (such as CO_2 concentration) very difficult. Therefore, time-lapse changes measured against a baseline survey are used to monitor fluid migration.

Two wells (OB-C1 and OB-C2) have been drilled specifically for monitoring CO_2 migration. Pre-injection baseline seismic measurements were obtained with a high-frequency piezoelectric source (1-5 kHz) and a low-frequency orbital source (50-400Hz) survey between wells OB-C1 and OB-C2. Two-dimensional tomographic images of p-wave velocity for both the low-frequency and high-frequency pre-injection seismic crosswell experiments have been calculated. These results are shown in Figure 3, with an interpreted cross section (provided by Chevron USA) shown in between. The high-frequency piezoelectric data set has higher resolution, as expected. A low-velocity zone is seen between a depth of 1,600 and 1,700 ft. in the high-frequency data. The apparent dip of this zone may be indicating the faulted offset seen in the cross section. The presence of a fault within the vicinity of the injection well provides an interesting opportunity to detect flow up the fault from one reservoir compartment to another.

Application of Natural and Introduced Tracers for Optimizing Value-added Sequestration Technologies

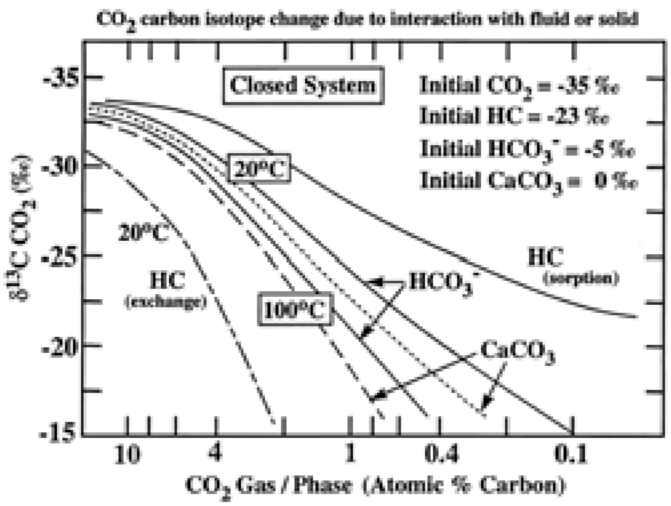
The overall goal of this effort is to provide methods that utilize the power of natural and introduced tracers to determine the fate and transport of CO_2 injected into the subsurface. The resulting data will be used to calibrate and validate predictive models used for (1) estimating CO_2 residence time, reservoir storage capacity, and storage mechanisms; (2) testing injection scenarios for process optimization; and (3) assessing the potential leakage of CO_2 from the reservoir.

Figure 3. Initial velocity tomograms using low- (left) and high-frequency (right) sources.



Stable isotopes of carbon can be used to track CO_2 migration and interactions with reservoir fluids and rocks. Experiments and model calculations have been conducted to assess the magnitude of carbon isotope change as injected CO_2 reacts with potential reservoir phases. An example of one set of calculations is shown in Figure 4, for a case where CO_2 is allowed to interact (in varying portions) with either a HCO_3-bearing brine, calcite, or hydrocarbon-rich rock (HC; Lost Hills) of unspecified composition. In a simplistic way, the extreme left-hand side of the figure can be thought of as the injection point for the CO_2, which undergoes reaction with progressively more and more of a particular carbon source during transport through the reservoir (left to right across the figure). In all cases, the carbon isotope values of CO_2 become less negative through reactions with either aqueous HCO_3, calcite, or HC. The carbon isotope trajectory is determined by temperature, which fixes the fractionation factor between CO_2 and any coexisting phase and the relative proportion of carbon in CO_2 to the carbon in the interacting phase. All of the cases shown are for binary systems (e.g., CO_2 — calcite; CO_2— HCO_3^-). However, carbon isotope trajectories for CO_2 interacting with both HCO_3^- and calcite would lie between the respective binary curves for any given temperature scenario. Note that the carbon isotope trajectories for CO_2 interacting with HC-bearing rock vary considerably, depending on whether the process is controlled by equilibrium isotope exchange or sorption. Sorption is perhaps more realistic for low temperatures involving CO_2 injection into EOR or CBM systems.

Figure 4. Results of numerical calculations showing the change in $\delta^{13}C$ — CO_2 as a result of interacting with the reservoir fluids and rocks.



Introduced tracers also have the potential to help quantify the extent to which CO_2 is interacting with reservoir fluids and rocks. After evaluating the results of published laboratory and field-tracer studies, gas tracers that appear to have the physical and chemical properties that would make them appropriate for field-scale tracing of injected CO_2 have been selected. Important selection criteria include: (1) low to zero concentration in the subsurface; (2) detectable at very low concentrations (parts per trillion or less); (3) stable under reservoir conditions; (4) environmentally safe; (5) subject to some of the same mass-transfer processes as the injected CO_2; and (6) amenable to analysis using a single sample and a single method for the entire suite. Based on published studies, SF_6 and a suite of perfluorocarbons meet these criteria and will be tested in column studies. Results of these column studies will be used to further select the best choice for field-scale CO_2 testing and application. The basic design for a flow-through column apparatus has been developed that will allow us to test the relative interactions of the gas tracers with a variety of reservoir materials and under a range of pressure and temperature conditions appropriate for proposed injection scenarios.

Enhancement of Numerical Simulators for Greenhouse Gas Sequestration in Deep, Unminable Coal Seams

The goal of this effort is to improve simulation models for capacity and performance assessment of CO_2 sequestration in deep, unminable coal seams. Sample problems are being run with a number of commercially available simulators to determine the comparative performance of different approaches for simulating CO_2 enhanced coal bed methane production (Law et al., 2000). Features and processes requiring more accurate representation will be identified and approaches for improving the models will be developed.

Intercomparison of Reservoir Simulation Models for Oil, Gas, and Brine Formations

The objective of this effort is to stimulate the development of models for predicting, optimizing, and verifying CO_2 sequestration in oil, gas, and brine formations. The approach involves: (1) developing a set of benchmark problems, (2) soliciting and obtaining solutions for these problems (3) holding workshops of industrial, academic, and laboratory researchers, and (4) publishing results.

The first set of test problems have been developed and are listed in Table 3 (Pruess et al., 2000). These problems have been widely distributed to the scientific community, and researchers from nine organizations (including researchers from France, Canada, Norway, Australia, and the Netherlands) have indicated an interest in participating in Phase 1 of the code intercomparison study. Over time, as more laboratory and field data become available, test problems will evolve to address greater complexity and validate experimental data. More information about the code intercomparison project can be found at http://www-esd.lbl.gov/GEOSEQ/code/.

Table 3. First set of test problems for code intercomparison study.

Process	Problem Title
Carbon sequestration with enhanced gas recovery	1. Mixing of stably stratified gases 2. Advective-diffusive mixing due to lateral density gradient
Sequestration in deep brine-filled formations	3. Radial flow from a CO_2 injection well 4. CO_2 discharge along a fault zone 5. Mineral trapping in a glauconitic sandstone aquifer 6. CO_2 injection into a 2-D layered brine formation
Hydro-mechanical coupled processes	7. Hydro-mechanical responses in the caprock and formation during CO_2 injection
Sequestration in oil reservoirs and CO_2 EOR	8. CO_2-oil displacement and phase behavior

Improve the Methodology and Information Available for Capacity Assessment of Sequestration Sites

The objectives of this task are to: (1) improve the methodology and information available for assessing the capacity of oil, gas, brine, and unminable coal formations; and (2) provide realistic and quantitative data for construction of computer simulations that will provide more reliable sequestration-capacity estimates.

Initial efforts in this activity focused on performing an assessment of the capacity for sequestration of all the CO_2 generated from fossil-fuel-fired power plants in California (Benson, 2000). California has a population of 34 million people and supports an economy of $1,280 billion, placing it among the top 10 economies in the world. Covering over 411,469 km^2, California encompasses a diversity of geologic terrains, from the volcanoes of the Cascade Mountain range in the north to the deep sedimentary troughs in the Central and Imperial Valleys in the south, from the Sierra Nevada Mountain range to the east and the 1500 km coastline to the west. Rich in natural resources, it is the fourth largest oil and gas producer in the United States, with extensive groundwater and surface-water resources. All of these features make California attractive for a regional case study to assess the feasibility of geologic sequestration of CO_2.

Current annual CO_2 emissions from fossil-fuel combustion in California total 380 million metric tons (MMT), of which 56.5% are from transportation, 16.2% from electrical generation, 14.4% from industrial sources such as refineries and cement kilns, 8.5% from residential heating and cooking, and 4.4% from commercial uses. Over 95% of the emissions from electrical generation come from oil/gas fired power plants. Thus, this study focuses on assessing the feasibility of sequestering the 62 MMT of CO_2 emissions (16.24% of the total emissions) generated annually from oil/gas-fired power plants in California.

Three types of reservoirs that may be suitable for sequestration were evaluated: (1) active or depleted oil fields, (2) active or depleted gas fields, and (3) brine formations. Based on a volumetric analysis of sequestration capacity and current CO_2 emission rates from oil/gas-fired power plants, the calculations presented in Table 4 suggest that oil reservoirs, gas fields, and brine formations can all contribute significantly to sequestration in California. Together they could offer the opportunity to meet both short- and long-term needs. In the near term, oil and gas reservoirs are the most promising because the trapping structures have already stood the test of time and opportunities exist for offsetting the cost of sequestration with revenues from enhanced oil and gas production. In the long term, if the trapping mechanisms are adequately understood and deemed adequate, brine formations may provide an even larger capacity for geologic sequestration over much of California.

More thorough assessments of sequestration capacity are now being made for the brine-filled Frio and Oakville Formations in Texas (Hovorka et al., 2001). Detailed two- and three-dimensional simulations that include realistic descriptions of the formation heterogeneity and regional geology are being performed.

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Table 4. Calculations of the sequestration capacity of oil, gas and brine formations in California. The estimated capacity is expressed in terms of the number of years capacity at the current emission rate of 62 MMT CO_2 per year.

Formation Type	**Estimated Capacity**	**Off-setting Revenues**	**Comments**
Oil	5 to 40 years (20 to 80 years)	Yes	• Large, deeper oil fields provide best opportunity • Smaller fields may be cost-competitive if combined with EOR
Gas	5 to 10 years	Possibly	• Large gas fields provide the best opportunity
Brine	> 350 years	No	• Long lead time to begin commercial-scale operation

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