2. Storage Monitoring And Verification (SMV) Studies

Task - 4.0 - Establish Key Geologic Controls & Requirements

The CCP-SMV program is comprised of four major technology areas:

- Integrity – evaluation of natural and engineered systems and their suitability for CO_2 sequestration,
- Optimization – realizations of efficiencies and tradeoffs that improve the economics of CO_2 sequestration,
- Monitoring – the development of performance evaluation tools and safeguards in the CO_2 sequestration "life cycle" and
- Risk Assessment – identification and quantification of HSE risks associated with CO_2 sequestration.
- A fifth program comprises an effort to integrate results of the studies and strategies for their dissemination outside of CCP.

Since CCP's inception in 2000, the SMV program has contracted 33 studies, including NGCAS (6 projects). Presently, nine of these studies are complete, sixteen have been active since before early 2003 and eight are newly contracted in the present reporting period. Most projects will be completed by the end of 2003 with the exception of NGCAS (European Union funded) and, possibly, some of the Risk Assessment projects. The following is an overview of the progress of the SMV projects for the present reporting period

Integrity

Integrity studies include examination of competent and incompetent natural systems for CO_2 storage, CO_2 exposure experiments on natural reservoir and cap-rocks and well materials and predictive modeling of reservoir / cap rock response to CO_2 injection.

Two studies use natural geologic systems to characterize competence to store CO_2. Prototypically incompetent geyser systems from the East-Central Colorado Plateau are examined for features that preclude effective CO_2 storage (Utah State University; Evans). Detailed geologic, hydrologic and geochemical work showed that despite the potential for fault gouge sealing or sealing by mineralization of fractures and faults, the geyser systems have been releasing abundant CO_2-charged water since the early Tertiary. The chemistry showed that the system is fed meteoric water, which reacts to release CO_2 from minerals. CO_2 evolves from the water as it travels to shallower depths up through the fault system. In contrast, the naturally occurring CO_2 fields assessed by ARI (Stevens) have apparently hosted CO_2 for geologic-scale time periods. Structural and stratigraphic characteristics as well as details on reservoir and cap rock systems will define features favorable to CO_2 accumulation and retention. As some of these fields are operated to produce CO_2, valuable information on drilling, performance and safety will become available.

Experiments on reservoir and seal rocks under reservoir pressure and temperature are ongoing at GFZ-Potsdam (Borm). The purpose of these experiments is to ascertain physical and chemical transformations that alter rock properties with CO_2 exposure. There is evidence for changes in the physical strength of the rocks, possibly due to mineralogical transformations (dissolution and precipitation). This study offers an opportunity to history match the reactive transport modeling project conducted by LLNL (Johnson).

Geomechanical modeling by APCRC (Rigg) will add further to our capability to predict rock response to the physical and chemical effects of CO_2 injection into reservoirs.
The susceptibility of well materials (cement and steel) to weakening by erosion / corrosion or strengthening by scaling / mineral precipitation in the presence of elevated CO_2 addresses perhaps the weakest link in CO_2 containment (Lindeberg, SINTEF). The study reveals both types of responses to stagnant and moving CO_2. Recommendations for new, less susceptible well materials, completion procedures and intervention will be included in the final study.

The integrity program has identified the principal weaknesses to CO_2 containment in natural and engineered systems. The obvious solution includes careful evaluation of natural systems using analogs and experiments and the development special well materials / construction and remediation.

Optimization

Optimization studies attempt to identify more efficient ways to store CO_2 in settings familiar to the oil and gas industry (e.g., EOR and EGCR), anticipate difficulties in CO_2 storage in other venues (e.g., aquifers) and look for economic tradeoffs with the CO_2 capture.

There is extensive CO_2-EOR experience in the Permian Basin of West Texas. The survey conducted by the New Mexico Institute of Mining and Technology (Grigg) identified areas for improvement in CO_2 EOR operations that have implications for CO_2 storage. Recommendations include further research on CO_2 injectivity, conformance, monitoring and remediation. Further work could also examine the ultimate storage capacity of these reservoirs as well as leakage detection and rates.

The Texas Tech University (Frailey / Lawal) and Tieline Technology (Stenby) studies address phase behavior of CO_2 in gas and gas condensate reservoirs and in oil reservoirs (respectively). The Texas Tech study is expected to produce software that will predict the CO_2 storage capacities of reservoirs and the potential for EGCR. The Tieline Technology software predicts CO_2 gas behavior in oil reservoirs.

An extensive survey of Canadian and European natural gas storage experience has been compiled by GTI (Perry). Although the focus of this work was on leakage identification and remediation, there are valuable insights into geological features that make such operations successful. Issues identified are keyed to how the CO_2 storage might be impacted. As with the natural gas storage experience in the USA, it is remarkable how few incidents have been reported. The hazard levels anticipated from CO_2 storage would seemingly be less, given that the technology to identify appropriate storage venues are improving and CO_2 is not flammable.

Predicting the behavior of CO_2 injected into reservoirs is complex and varies with state (i.e., supercritical versus non-supercritical), water salinity and reservoir architecture. The study by the University of Texas (Pope) begins to characterize storage performance of CO_2 in aquifers by looking at brine density transformations and mineralization. Simulation studies will identify reservoir / brine suitability criteria that will influence operating procedures. To date, a base case simulation has been run for a generic aquifer with sensitivity analysis of reservoir parameters such as permeability (mean, vertical, and horizontal), residual gas saturation, salinity, and temperature. Initial findings show that residual gas saturation will significantly impact the strategy used in CO_2 sequestration.

A baseline for piping, compression and injection systems needed to transport CO_2 is the topic of the Reinertsen Engineering study. An optimization of materials and necessary hydration levels will be the product of this study.

Economic tradeoffs between the purity of CO_2 (with various levels of SOx and NOx) captured at the surface and the behavior of impure CO_2 in the subsurface are the topics of studies by Battelle (Gupta) and The University of Texas (Bryant), respectively. In the surface study, possible untoward effects on amine

and other solvent systems and piping and compression equipment will be evaluated. Subsurface phase and solubility behavior of impurities and their effects on subsurface equipment and reservoirs will be estimated in the subsurface study.

These optimization studies, once integrated and attached to realistic scenarios, will be of considerable value in approaching workable CO_2 capture, transportation and storage programs.

Monitoring

Numerous remote (satellite and aerial), geophysical and geochemical approaches to monitoring CO_2 storage performance and leakage / seepage have been proposed. The resolution and expense of these techniques varies considerable. The principal goal of the monitoring studies is identify the most useful and cost effective approaches.

TNO (Arts) presents a comprehensive, comparative survey of monitoring technologies in addition to seismic modeling of aquifer CO_2 storage (Sleipner-like) and ECBM. The applicability of various monitoring techniques to caprock leakage, ground movement, lateral spreading, and verification/mass balance were rated. Further seismic modeling of CO_2 storage is recommended with a focus on escape scenarios.

LBNL (Hoversten) provides field, experiment, model and theoretical examples of novel non-seismic geophysical monitoring techniques. Recent highlights of this study include an effort to test the spatial resolution of geophysical monitoring approaches to a reservoir simulation model on Schrader Bluff (North Slope, Alaska) and the laboratory demonstration that streaming potential (SP) induced by flowing CO_2 through core samples might be measurable at the surface in a field CO_2 storage project. Ongoing work includes surface seismic, AVO analysis and electromagnetic modeling.

The single geochemical-based monitoring project investigates the use of noble gas isotopes as tracers and leakage indicators. The CO_2 EOR Mabee Field of West Texas is used as an example application. To date, the proposed optimal system involves Xenon, the isotopes of which allow a distinction among air, subsurface gases and the supply gas. Doping of supply gas with such chemically distinctive gases allow, in addition to tracing CO_2 conformance, a means to establish ownership of leaked gas is made available. The amount of gas needed for a test of the system has been calculated. The remaining tasks include details of a protocol for noble gas injection and testing of a gas transport model.

The early study by Tang (CalTech) evaluated the state-of-the-art in atmospheric monitoring technologies. A follow-up study aims at identifying technologies capable of detecting leakage rates as small as 1% and developing scenarios at which such techniques might be applicable.

The satellite radar interferometry (InSAR) study by Stanford University (Zebker) involved working up the theoretical resolution of ground movement due to CO_2 injection into a hypothetical reservoir. The resolution (~1 cm) is comparable to tiltmeters and time lapse GPS but is thought to have advantages in the abundance of data available and large coverage area. Some work was done on estimating reductions in resolution due to atmospheric and topographic effects.

Satellite and aerial hyperspectral analysis of plant stress and mineral anomalies, thought to be induced by high surface CO_2 concentrations, were investigated by LLNL (Pickles). A satellite application was presented for Mammoth Mountain, CA where tree kills from a volcanic-related CO_2 release was confirmed. An aerial survey of the CO_2 EOR Rangely Field, CO, has been examined for anomalies and a field trip is planned to determine what features might be associated with these anomalies.

A recently contracted study will evaluate the near surface approaches to detect CO_2 leaks (Davis, Penn State). The favored technology, IR laser, will be evaluated for capability of measuring near surface vertical turbulent flow of CO_2.
A broad range of monitoring technologies has been investigated for the monitoring program. Future research direction will focus on the few most promising remote / aerial, near surface and subsurface approaches. Additional programs should also include direct analyses of subsurface fluids (e.g., well water and gas sample analysis, soil gas analysis).

Risk Assessment

Risk assessment was identified as a critical research area early in the SMV program. Initial studies contracted and completed include an HSE assessment and lessons learned by other industries involved in the disposal of industrial wastes or storage of natural resources (Benson, LBNL) and one focusing on political and regulatory lessons learned by the nuclear waste industry. Subsequently, three large risk assessment methodologies development studies evolved and are ongoing (Wildenborg, TNO; Liang, INEL; Oldenburg, LBNL). The status of these projects is summarized below. An additional study, involving reactive transport modeling to assess transformations in reservoir and cap-rocks, is also summarized but the results are also applicable to the "Integrity" program outlined above.

The TNO study has proposed two scenarios to test their risk assessment methodology (Southern North Sea aquifer and onshore Netherlands gas field). Extensive work has been done on FEPs (features, events and processes) that is now destined to become a standard, shared database. A Monte Carlo simulation (>1000 parameter combinations) of a reservoir seal model has recently been successfully completed. Simulations of a shallow subsurface / surface (atmosphere) model were conducted recently with LBNL (Oldenburg). A grid convergence problem was noted and is being resolved. The probabilistic tool developed earlier in 2003 was tested and found to be user friendly and fast. The globality parameter, which determines the "radius of influence" of various data points, however, was found require further expert input and sensitivity studies. Work continues on collecting data needed to run simulations of the two scenarios.

The coal bed-based (ECBM) risk methodology by INEL (Liang) continues apace in conjunction with a larger San Juan Basin coal bed methane storage capacity study. Geomechanical studies have elucidated mechanisms for gas leakage from fractures in coal and its overburden. Relative risks of poorly designed fracturing attempts and uncemented versus cemented wells have been estimated. A mechanistic field model matched to field performance revealed the sensitivity of coal reservoir properties to performance in terms of gas and water permeability and gas / water ratios. Using the larger Fruitland coal seepage model, simulations suggest guidelines for locating injection relative to the water table and outcrops.

The near surface / surface coupled CO_2 flow model by LBNL (Oldenburg) shows good agreement with the commercial FLUENT model for surface-layer diffusion and agrees with empirical correlations for density-dependent flow. Other simulations show that atmospheric dispersion of CO_2 is twice as large when modeled in 3D as opposed to 2D. The coupled model framework will be used to estimate CO_2 fluxes and concentrations for various leakage and seepage scenarios.

The reactive transport modeling by LLNL (Johnson) incorporates coupled thermal, hydrological and geochemical processes to address key technical issues related to cap rock integrity (particularly that associated with the well bore) in aquifer storage of CO_2. Significantly, there is evidence for continuous improvement of hydrodynamic seal integrity via mineral trapping mechanisms. Proof of this concept will be approached using the experimental results of GFZ-Potsdam (Borm).

Maintaining progress in the risk assessment studies requires close supervision and collaboration among the research groups. An effort has been made to ensure that the programs are mutually aligned in the

sense that they all include the essential elements of scenario development, hazard identification and probability and simulation.

Integration and Communication

A plan for integration and dissemination of SMV research results, coordinated with that of the larger CCP program, is in progress. LBNL (Benson) has been contracted to arrange publications at the technical specialist, general scientific / engineering, government / regulator, NGO and general public levels. The workshop planned for September 22-25, 2003 in Dublin, Ireland will bring together final plans for this effort.

2.1 Risk Assessment and Analysis

Task - 4.5 Risk Assessment and Mitigation Options

Risk assessment is fundamental to public acceptance and ultimate deployment of geologic CO_2 sequestration. Risk assessment is based on the ability to predict the likelihood of significant CO_2 release from the reservoir and its impact on plants, animals and humans. Those organizations and businesses wishing to use geologic carbon sequestration as a means to reduce the CO_2 emission impacts on the environment will have to demonstrate that they have evaluated these risks and taken steps to ensure that the public is protected. A key activity in the risk assessment portfolio of projects is to develop methodologies and tools to evaluate those risks and to develop monitoring tools that allow for early detection and remediation. It is essential that the whole process be clear and transparent to both the public and to regulators.

The CCP Storage, Monitoring and Verification (SMV) program includes eight projects, six of which are co-funded by DOE. There are two literature and policy reviews, completed prior to the present reporting period, that cover "lessons learned" from geologic disposal of industrial materials in general (LBNL, Benson) and the nuclear waste in particular (Monitor Scientific, Stenhouse). The studies by TNO (Wildenborg), INEL (Liang), and LBNL (Oldenburg) entail development of risk assessment methodologies. The LLNL (Johnson) study uses reactive transport modeling to predict cap-rock integrity. The major findings of the completed and current risk assessment studies are outlined below.

In "Lessons Learned from Natural and Industrial Analogs for Storage of Carbon Dioxide in Deep Geologic Formations" (LBNL, Benson), information related to HSE effects of CO_2 exposure and the history, status and issues associated with disposal of industrial waste and storage of natural gas are reviewed. With respect to CO_2 storage, the review offers a valuable perspective to how to proceed with establishing safeguards and engaging regulators and the public.

In "Lessons Learned from Nuclear Waste Disposal" (Monitor Scientific, Stenhouse), the results of past efforts achieve regulatory approval and public acceptance of nuclear waste disposal in the US, Canada and Europe were reviewed. In addition to having robust technical designs prepared, such efforts require early stakeholder involvement and transparency in decision-making. Although CO_2 storage is clearly much less risky than nuclear waste disposal, the process for gaining approval of individual projects must be approached in a similar fashion.

The objective of the TNO "Safety Assessment Methodology for CO_2 Sequestration" (SAMCARDS) is to develop a methodology and computational tools for HSE risk assessment of geological CO_2 sequestration in example geologic venues (offshore aquifer and onshore gas field) in the southern North Sea. Although assessments will be performed on specific sites as deliverables, the overall methodology is expected to comprise a generic framework for site characterization, risk mitigation, remediation and monitoring of a given storage facility. In the period reported here, tools have been developed that allow consistent analysis of an FEP (features, events, processes) database and therefore identify groups of scenario-defining FEPs for a given site. A June 2003 workshop showed that once necessary adjustments are made to the tools, base case scenarios and variants thereof can be defined. Monte Carlo simulations of the reservoir seal model, carried out with > 1000 parameter combinations was successful. Simulations of a shallow subsurface / surface (atmosphere) model (conducted with LBNL, Oldenburg) reveal a grid convergence problem which needs to be worked out. The probabilistic tool that will form the basis of the performance assessment model has been finalized and shown to be fast and easy to work with. The important "globality" parameter, which determines the "radius of influence' of various data points, still requires expert input. The sensitivity of the probabilistic model to the choice of the globality parameter needs further examination.

The "Methodology for Conducting Probabilistic Risk Assessment of CO_2 Storage in Coal Beds" by Liang(INEL) aims to develop the knowledge, tools, and strategies for risk evaluation, risk mitigation and monitoring / verification for CO_2 - Coal Bed storage. The methodology is being developed in the context of the Tiffany Field (BP, San Juan Basin, CO) enhanced coal bed methane gas injection (presently N_2) demonstration project. The work scope includes data acquisition / knowledge gaps, predictive quantitative modeling and consequence analysis / risk prediction. For the present reporting period, a geomechanical study was performed to evaluate factors that lead to risks of developing CO_2 leakage paths at each stage of the methane producing operation. Risk factors identified include operating without cement well casing and poorly selected fracturing procedures. The process of depressurization during dewatering followed by repressurization with CO_2 likely leads to leakage via coal failure and preexisting slip discontinuities in the coal and overburden. A mechanistic field model was developed to match field performance of a Tiffany Filed 5-spot pattern. Findings from a sensitivity study of key coal reservoir properties showed: the importance of history matching coal methane content data, the influence of cleat porosity and permeability to gas / water production ratios and the effect that early N_2 injection has on coal fracture patterns and consequent methane and CO_2 conformance. In a representative seepage model for the Fruitland coal, simulations show the importance of injection location relative to the water table and outcrops to avoid leakage.

The Lawrence Berkeley National Laboratory (Oldenburg) study on "Leakage and Seepage from Geologic CO_2 Sequestration Sites" is a coupled model that handles subsurface and atmospheric surface-layer flow and transport. The coupled model shows good agreement with the commercial fluid dynamics code FLUENT for surface-layer dispersion and agrees with empirical correlations for density-dependent flow. Simulations demonstrate that dilution of CO_2 by atmospheric dispersion is approximately two times larger in 3D than in 2D. The coupled model framework can be used to estimate CO_2 fluxes and concentrations for risk characterization of various leakage and seepage scenarios.

In the "A Risk Assessment Methodology for Geologic CO_2 Storage: Reactive Transport Modeling to Predict Long-Term Cap-Rock Integrity" study (LLNL, Johnson), an advanced computational package is used to treat coupled thermal, hydrological and geochemical processes to address key technical issues associated with CO_2 storage in saline aquifers. Foremost among these issues is the integrity of cap-rocks in the vicinity of the well bores. Recent work has shown that the hydrodynamic seal integrity of shale cap-rocks is continuously improved by mineral trapping mechanisms. Proof of concept might involve simulation to match core flood experiments or natural analogs.

With earlier completed studies as an underpinning, the SMV Risk Assessment Portfolio covers key technical HSE issues related to geologic CO_2 sequestration. The TNO and ECL (European NGCAS) studies have been aligned and are benchmarking of all major methodologies within CCP to those from other JIPs is expected this year.

2.1.1 Safety Assessment Methodology for Carbon Dioxide Sequestration (SAMCARDS)

Task - 4.5 - Risk Assessment And Mitigation Options
Principal Investigator: Ton Wildenborg
Technology Provider: TNO-NITG

Highlights

- Tools were developed that allow consistent analysis of the FEP database, and hence the development of methods to identify groups of scenario defining FEP's.
- Testing during a two-day workshop in June 2003 showed, that adjustments in the tools and the FEP database are still needed. With these adjustments the base case scenario and variant scenarios can be defined.
- Monte Carlo simulations with the reservoir-seal model have been carried out for some 1,000 combinations of parameter values. No major problems were encountered in carrying out these simulations.
- Simulations for the shallow subsurface model, including the atmosphere, are carried out by LBNL. The first results of these simulations are now being evaluated and discussed. These results indicate that there is a grid convergence problem, i.e. results are still dependent on spatial resolution of the model.
- The probabilistic tool that will form the basis of the Performance Assessment model has been finalized. The first tests show that the tool is easy and fast to work with. One of the major parameters in the model is the globality parameter that determines the "radius of influence" of the different data points. Choosing this parameter is a question of expert judgment. It needs to be seen how sensitive answers of the probabilistic tool are for the choice of this globality parameter.

Summary
The objective of the project Safety Assessment Methodology for Carbon Dioxide Sequestration (SAMCARDS), conducted by TNO-NITG of the Netherlands, is to develop a methodology and computational tools for HSE risk assessment of geological CO_2 sequestration in various geological media of the North Sea region. The main deliverable, consisting of risk assessment method and computational tools, will be suitable for site-specific assessment of geological sequestration projects, in particular storage in an offshore aquifer and storage in an onshore gas field. The methodology is to be applied in a generic performance assessment of two European sequestration scenarios, one defined by CCP JIP and one introduced by TNO-NITG. The results of the generic safety assessment will provide building blocks for site characterization, risk mitigation, remediation and monitoring of the storage facility.

FEP analysis and scenario formation

The SAMCARDS FEP database that was reported in the previous semi-annual report consists of some 665 different FEP's. Analyzing this comprehensive set of FEP's in terms of interactions, relations and grouping will require, apart from expert judgment, a lot of effort. In fact, such an analysis is virtually impossible without the aid of a number of tools that allow for a consistent treatment of these FEP's. These tools have now been developed. They allow visualization of interactions between FEP's and relations between the different FEP's. They also allow the grouping of FEP's based on information available in the database. However, even though these tools are a necessity, analysis of the FEP's and grouping them into scenario defining elements cannot be done without expert judgment.

During a two-day workshop held in June 2003, a number of experts were requested to work with these tools and analyze the FEP's that were previously screened and, if possible, define groups of FEP's that form scenario elements. The workshop showed that, in principle, the different abstraction levels of FEP's makes it in some cases difficult to define interactions between them. The fact that definitions are not always clear, and that there sometimes still is considerable overlap between the FEP's does not help either. Thus, definitions and rules with respect to the screening of the FEP's are not always clear and need further documentation. Apart from small adjustments in the tools, the possibility to show circular relations in the influence diagrams may need to be implemented. With these adjustments and developments the definition of scenarios should be possible using the previously mentioned tools.

Integration with the Weyburn FEP database and placing it on a public web-site (IEA Greenhouse Gas R&D Programme) is desirable and will be on the program for the next period, provided funding becomes available.

Process modeling

Based on the sensitivity analysis reported in the previous semiannual report, Monte Carlo simulations have been carried out for the reservoir-seal model without encountering problems. Some 1,000 combinations of parameter values were generated, and CO_2 fluxes that must serve as boundary conditions for the shallow subsurface model have been calculated for these different combinations. Monte Carlo simulations are needed because the different compartments all suffer from the fact that the physical/chemical/mechanical parameters required for these models are in general highly uncertain. Thus, a stochastic approach has to be taken. Because of the non-linearities of the models, this will require Monte Carlo simulations with the different compartment models.

Simulations for the shallow subsurface compartment, including the atmosphere, are being carried out by LBNL. The first results are now being discussed and evaluated at the moment. They seem to indicate that the spatial resolution of the model still plays a role, i.e. that no grid converged solution was obtained with a course grid. This problem needs to be resolved in order to make Monte Carlo simulations with the shallow subsurface model possible. Furthermore, in contrast to what was reported in the previous semi-annual report, CO_2 spreads much further in the aquifer and enters the atmosphere. That has to do with an error in the definition of the CO_2 flux boundary conditions in the previous simulations. The first results obtained now indicate a strong dependence of the results on the calculational grid used. Further discussions with LBNL are required to solve that problem.

The development of the probabilistic Performance Assessment model has been finalized. Documentation, both of the scientific background and the computer program are available (Wojcik and Torfs, 2003a, 2003b). One of the important parameters in the probabilistic model is the globality parameter that in effect determines how far the influence of the different data points reaches. How sensitive results of the probabilistic model are for values of the globality parameter needs to be tested further. The model was tested with the results of the Monte Carlo simulations of the reservoir-seal model. The test showed that the probabilistic tool is easy to work with. Although it is almost impossible to visualize the multi-dimensional (in this case four dimensional) probability density functions, it is easy to generate individual probabilities, e.g. the probability that the CO_2 flux exceeds a certain limit. These probabilities are generated by Monte Carlo type simulations with the multi-dimensional probability density function, and these can easy and fast be carried out.

Publications

- Wojcik, R. and Torfs, P., 2003a "Fitting multidimensional Parzen densities with the use of a Kullback-Leibler penalty." Submitted to: Journal of the American Mathematical Society.

- Wojcik, R. and Torfs, P., 2003b “Manual for the use of the PARDENS tool.” Wageningen University and Research Centre.
- The semiannual progress report for this project is in Appendix A under the same heading as this summary.

2.1.2 Probability Risk Assessment Methodology for CO_2 Injection into Coalbeds

Task - 4.5 - Risk Assessment And Mitigation Options
Principal Investigator: Jenn-Tai Liang
Technology Provider: INEL

Highlights

- A study was performed to evaluate geomechanical factors that need to be taken into account in assessing the risk of CO_2 leakage in CO_2 sequestration in coal beds. Geomechanical processes lead to risks of developing leakage paths for CO_2 at each step in the process of developing a coal bed methane project for methane production and eventual CO_2 sequestration. Though each of the risks identified in this study needs to be evaluated for specific sites, some general conclusions have been drawn from this review.

- Reservoir Simulations to Support Risk Characterization was completed. The mechanism, by which CO_2 can enhance the coalbed methane recovery and at the same time sequester CO_2 in coal matrix, is a complex physical and chemical interaction process. More research in both laboratory experiments and field demonstrations are needed before CO_2 sequestration in coal can become an applicable industry practice. Consequently, future improvements to simulation models are also needed, especially in modeling coal structure reactions to gas injection and the multiple component adsorption/desorption processes.

Summary

The goal of this project is to provide a methodology acceptable to regulators and the public alike by which to conduct a meaningful probability based risk assessment of CO_2 injection and storage in coal beds. Consequently, the work is developing the necessary knowledge, tools, and strategies for risk evaluation, risk mitigation, monitoring, and verification. The work is conducted within the context of an actual field demonstration of the technology employing field data from BP's Tiffany project in the San Juan Basin, Colorado. To date, BP's Tiffany project is the only commercial scale enhanced coal bed methane recovery by gas injection in the US. The work scope of this project includes three major task areas:

- Data acquisition/knowledge gaps;
- Predictive quantitative modeling;
- Consequence analysis and risk characterization.

Geomechanical Study (Task 1.0.3)

Wellbore stability is a geomechanical problem that can be encountered during drilling of the well. Weak shale layers, weak coal layers, overpressure, and faults zones are common causes. Rock failure and displacements associated with wellbore instability generate potential leakage paths in the vicinity of the well. Cementing the casing minimizes the risk of leakage. Risks of leakage are much higher for open cavity completions than for cased well completions. Careful selection of fracturing technology for well completion that account for the specific coal properties should minimize the risk that hydrofractures grow out of the desired interval. Techniques to monitor fracture height need further development.

The processes of depressurization during dewatering and methane production, followed by repressurization during CO_2 injection, lead to risks of leakage path formation by failure of the coal and

slip on discontinuities in the coal and overburden. The most likely mechanism for leakage path formation is slip on pre-existing discontinuities that cut across the coal seam. Relationships between the amount of slip and the increase in flow (if any) along a discontinuity need to be developed.

Predictive Quantitative Modeling (Task 2.0.2)

In this study, the focus of quantitative modeling was placed on an actual field case (Tiffany field), the sensitivity study of key coal reservoir properties, and CO_2 seepage from outcrops. This approach establishes a linkage between the first-hand knowledge of the actual field performance and a more realistic CO_2 seepage forecast. For comparison and validation purpose, two reservoir simulators were used, the BP-Amoco GCOMP and the COMET2, developed by Advanced Resources International.

A mechanistic field model was developed to match the field performance of a 5-spot pattern in the northern part of the Tiffany Field where BP-Amoco is conducting nitrogen injection to enhance methane recovery and plans to perform a micro-pilot CO_2 injection test. By matching the nitrogen breakthrough times and nitrogen cut, simulation revealed that the elevated pressure by N_2 injection caused the coal fractures on the preferred permeability trends not only to expand but also to extend from injectors to producers. Even in the low-pressure regions near the producers, the permeabilities were higher than expected. The model suggests that the future gas injection and CO_2 sequestration may be restricted to only one third of the total available pay. The model also predicted early inert gas (N_2 plus CO_2) breakthrough and high inert gas cut during future gas injections. The high volume of inert gas produced could overwhelm the reprocessing capability resulting in early termination of the project.

The findings from a sensitivity simulation study of key coal reservoir properties include:

1. Laboratory measured isotherms on dry coals should be rescaled by matching field history performance. Without rescaling, incorrect estimates of initial methane content calculation, CO_2 sequestration capacity in coal, and CO_2 or N_2 injection performance could result.

2. During the primary production, the gas to water production ratio is very sensitive to cleat porosity because the cleat porosity is usually very small and initially filled with water.

3. The permeability aspect ratio of face cleat permeability to butt cleat permeability could have a significant effect on gas and water production rates as demonstrated in history matching the five production wells in the Tiffany pilot area. 4)

4. The early N_2 breakthrough and high N_2 cut observed in the Tiffany field suggest that the elevated pressure during gas injection caused the coal fractures on the preferred permeability trends not only to expand but also to extend from injectors to producers. Consequently, the injected inert gas (CO_2 or N_2) may only contact a small portion of the entire pay volume. A dual model with one injection well and one production well on a 160-acre well spacing was used to simulate the effect of coal net pay thickness thereby the coal volume on the inert gas production cut. In comparison with the actual field performance, it suggests that only about one tenth to one fifth of the total pay interval may be contacted by injected inert gas (CO_2 or N_2).

A representative seepage model was developed for the Fruitland coal in Colorado portion of the San Juan basin. The model is a two-layer, 1.25 mile by 12-mile strip with a down dip of 2.92 degree from the up outcrop to the bottom of the basin. The model consists of two seepage wells to represent the 1.25mile outcrop and three water recharge wells placed just below the water table to represent the ground water recharge. Under preferable scenarios, if CO_2 injection wells are placed below and at least 2 miles away from the water table, simulations have predicted no significant change in methane seepage from outcropping formations with various CO_2 injection schemes. To simulate the worst-case scenarios, CO_2 injection wells have been placed above the water table. The results show that a large CO_2 and methane

breakthrough could happen if the CO_2 injection wells are too close, within 2 miles, to the outcrop. Consequently, any CO_2 injection within a distance of 3 miles from outcrop should be considered with high risk.

Publications

- No formal reports or presentations were made during the reporting period.
- The semiannual progress report for this project is in Appendix A under the same heading as this summary.

2.1.3 HSE Risk Assessment of Deep Geological Storage Sites

Task - 4.5 - Risk Assessment and Mitigation Options
Principal Investigator: Curt Oldenburg
Technology Provider: LBNL

Highlights

- A coupled modeling framework has been demonstrated for risk characterization. The coupled model handles subsurface and atmospheric surface-layer flow and transport assuming that dispersion in the surface-layer is passive and that the wind is described using a logarithmic wind profile.
- The coupled model shows good agreement with a commercial fluid dynamics code FLUENT for surface-layer dispersion, and agrees with empirical correlations for the transition from passive to active (i.e., density-dependent) flow.
- Coupled subsurface–surface-layer demonstration simulations show the large degree of dilution that occurs in the surface layer, and the possible reflux of CO_2 to the subsurface that occurs when CO_2 dissolves in infiltrating rainwater.
- Simulations show that dilution of CO_2 by atmospheric dispersion is approximately two times larger in 3-D than for similar 2-D results.
- This coupled modeling framework can be used to estimate CO_2 fluxes and concentrations for risk characterization of various leakage and seepage scenarios.

Summary

Risk assessment is fundamental to public acceptance and ultimate deployment of geologic carbon sequestration. Risk assessment is based on the ability to predict accurately CO_2 concentrations likely to impact plants, humans, and other animals.

The Site Specific HSE Risk Assessment Project goal is to develop and a test a model coupling ground leakage and atmospheric transport to evaluate the HSE risk for a range of CO_2 injection scenarios. Probabilistic estimates for the consequences of CO_2 leakage will also be developed. All aspects of risk assessment (RA) will be summarized using the coupled models and include a study of long term degradation or erosion and cross effects of cap rocks and two other geologic materials.

The project is investigating how CO_2 is transported through the geologic subsurface from the target formation along potential leakage paths. During the leakage process, significant attenuation due to secondary hydrodynamic trapping, solubility trapping, and dispersion is expected. When CO_2 reaches the shallow subsurface and seeps out from the ground, further dispersion will occur. We are investigating through numerical simulation the transport and dispersion processes associated with CO_2 leakage, seepage, and atmospheric dispersion. The results of these analyses will feed into the risk assessment framework development and application. We are developing a coupled modeling framework for HSE risk assessment for geologic sequestration of CO_2. The framework will couple the following (i) geologic description of the reservoir, caprock and shallower formations, (ii) simulation of subsurface CO_2 migration, (iii) CO_2 dispersion over the ground surface and into buildings, (iv) exposures to human and ecological receptors, and (v) risk characterization. The framework can be used to assess the risks to plants, humans, and other animals of various leakage and seepage scenarios.

The basis for the risk assessment is a detailed prediction of CO_2 concentration in space and time in both the subaerial and subsurface environments. Risk assessment of this type would normally be carried out prior to sequestration project development, although it could also be used to assess risks from known leakage from an operating storage reservoir. This framework will be demonstrated in this project through its application to the potential use of an onshore natural gas reservoir for carbon sequestration.

A coupled modeling framework was developed for simulating carbon dioxide (CO_2) leakage and seepage in the subsurface and in the atmospheric surface layer for risk characterization. The results of model simulations can be used to quantify the two key health, safety, and environmental (HSE) risk drivers, namely seepage flux and near-surface concentrations. The methodology and structure of the coupled modeling framework are based on the key concepts that

(1) the primary HSE risk is in the near-surface environment where humans, animals, and plants live,
(2) leakage and seepage flow processes are coupled, and
(3) the main risk drivers are CO_2 flux and concentration.

The coupled modeling framework is built on the integral finite difference multiphase and multicomponent reservoir simulator TOUGH2 and models CO_2 and air in both subsurface and atmospheric surface-layer regions simultaneously. The surface-layer modeling assumes CO_2 dispersion is passive and uses the logarithmic wind profile assumption and advective-dispersive transport equation. Surface-layer dispersivities are calculated from the Pasquill-Gifford curves and Smagorinski Model. We have tested the coupled modeling framework for gas-mixture physical property prediction, surface-layer transport and dispersion, and transition from passive to active flow.

The model for a coupled subsurface–surface-layer system was demonstrated and the large dispersion and dilution expected in the atmospheric surface layer was shown. Whereas CO_2 concentrations in the subsurface can be extremely high, surface layer winds easily reduce CO_2 concentrations to trace levels for the fluxes investigated. Even for calm conditions, density-driven CO_2 flow appears capable of preventing CO_2 concentrations from reaching significant levels over flat and horizontal ground surfaces. It is also observed in the demonstration problem that there is reflux of CO_2 by infiltrating rainwater containing dissolved CO_2, a process that shows the importance of using a coupled modeling framework. Finally, downwind concentrations were compared for 2-D and 3-D simulations of surface-layer dispersion and approximately a factor of two decrease in CO_2 concentration was observed for the 3-D simulation relative to the 2-D simulation.

Reports and Publications

- Oldenburg, C.M., A.J.A. Unger, R.P. Hepple, and P.D. Jordan, On Leakage and Seepage from Geologic Carbon Sequestration Sites, Task 1 Report, Lawrence Berkeley National Laboratory Report *LBNL-51130*, July 2002a.

- Oldenburg, C.M., T.E. McKone, R.P. Hepple, and A.J.A. Unger, Health Risks from Leakage and Seepage of CO_2 Sequestered in the Subsurface: Requirements and Design of a Coupled Model for Risk Assessment, Task 2 Report, Lawrence Berkeley National Laboratory Report *LBNL-51131*, July 2002b.

- Oldenburg, C.M., A.J.A. Unger, and R.P. Hepple, On Atmospheric Dispersion of CO_2 Seepage from Geologic Carbon Sequestration Sites, Task 3 Report, Lawrence Berkeley National Laboratory Report *LBNL-51734*, November 2002c.

- Oldenburg, C.M., D.H.-S. Law, Y. Le Gallo, and S.P. White, Mixing of CO_2 and CH_4 in gas reservoirs: code comparison studies, in proc. of GHGT-6, Kyoto Japan, Oct. 1–4, 2002, and Lawrence Berkeley National Laboratory Report *LBNL-49763*, March 2002d.

- Oldenburg, C.M., and A.J.A. Unger, Coupled subsurface-surface layer gas transport and dispersion for geologic carbon sequestration seepage simulation, Proceedings of the TOUGH Symposium 2003, Lawrence Berkeley National Laboratory, May 12–14, 2003, and Lawrence Berkeley National Laboratory Report *LBNL-52477*, May 2003a. (http://esd.lbl.gov/TOUGHsymposium/pdfs/OldenburgUnger.pdf)

- Oldenburg, C.M., and A.J.A. Unger, On leakage and seepage from geologic carbon sequestration sites: unsaturated zone attenuation, *Vadose Zone Journal*, in press, 2003b.
- The semiannual progress report for this project is in Appendix A under the same heading as this summary.

2.1.4 Synthesis Of Nuclear Waste Disposal Experience

Task - 4.1 Understanding Geologic Storage
Task - 4.5 Risk Assessment and Mitigation Options
Principal Investigator: Mike Stenhouse
Technology Provider: Monitor Scientific

Highlights

The study was completed and a final report was delivered to the project sponsors during the last reporting period.

Reports, Publications, and Presentations

- Final Report: Synthesis of Nuclear Waste Disposal Experience, Monitor Scientific. Mike Stenhouse

2.1.5 Reactive Transport Model: Caprock Integrity

Task - 4.1 - Understanding Geologic Storage
Principal Investigator: Jim Johnson
Technology Provider: LLNL

Highlights

- Recent technical focus has been to carry out and analyze a series of NUFT/LDEC simulations designed to address a fundamental question regarding natural CO_2 reservoirs: are they natural analogs to engineered CO_2 storage sites? There are important distinctions between the emplacement scenarios associated with natural and engineered sites that this modeling work suggests limit the extent to which these settings can be considered analogous—especially in terms of long-term cap rock integrity and isolation performance.

- The influx-rate dependence of pressure, effective stress, and aperture evolution within the cap rock has been modeled. These simulations suggest that geomechanical degradation of seal integrity will be characteristic of both natural and engineered CO_2 influx, but significantly more severe during the latter. This result implies that cap-rock isolation performance may vary considerably as a function of filling mode. When combined with the near influx-rate independence of geochemical alteration, which enhances the seal integrity of typical shale cap rocks, it further suggests that shales—during both natural and engineered CO_2 influx—may in fact evolve into effective seals during an initial leakage event.

Summary

The Reactive Transport Model for Caprock Integrity Assessment project aims to develop methodology and simulation capability for quantitative assessment of the relative long-term performance of potential caprocks for geologic storage of CO_2. The project will develop improved understanding of the various mechanisms by which CO_2 can penetrate caprocks and the time frame for caprock failure.

Reactive transport modeling is an advanced computational method for quantitatively predicting the long-term consequences of natural or engineered perturbations to the subsurface environment. Because these predictions typically involve space, time, and system complexity scales that preclude development of direct analytical or experimental analogs, they often represent a unique forecasting tool. The fundamental advance embodied in reactive transport modeling is its explicit integration of these conceptually distinct process models.

A unique computational package was developed that integrates a state-of-the-art reactive transport simulator supporting geochemical software and databases. In a series of recent studies, we have used this package—which treats coupled thermal, hydrological, and geochemical processes—to address a number of key technical questions regarding CO_2 storage in saline aquifers. Paramount among these is the issue of long-term cap-rock integrity, which represents the most important risk-assessment concern when evaluating potential sites.

Recent work has shown that the hydrodynamic-seal integrity of shale cap rocks is continuously improved by mineral trapping mechanisms, which reduce local porosity and permeability throughout active-injection and post-injection storage regimes. The ability to forecast long-term hydrodynamic-seal performance of cap rocks as a function of coupled hydrological, geochemical, and geomechanical processes will be a unique means of identifying optimal storage sites, where leakage potential is minimized.

Demonstrated efficacy of our simulation capabilities ("proof of concept") can be achieved through laboratory and field confirmation of predicted cap-rock porosity-permeability evolution. On the laboratory scale, it may be possible to simulate some of the experiments being conducted by Borm et al. On the field scale, it may be possible to simulate long-term evolution of cap-rock integrity for one or more of the "natural analog" sites under investigation by Stevens et al., which would provide a useful complement to the work on natural CO_2 accumulations.

Reports and Publications

- Johnson, J.W., Nitao, J.J., Morris, J.P., and Blair, S.C., Reactive transport modeling of geohazards associated with offshore CO_2 injection for EOR and geologic sequestration: *Proceedings Offshore Technology Conference 2003*, Houston, TX, May 5-8, 2003, 9 p.
- Johnson, J.W., Nitao, J.J., and Morris, J.P., Reactive transport modeling of cap rock integrity during natural and engineered CO_2 sequestration: American Chemical Society National Meeting, New York, NY, September 7-11, 2003
- Johnson, J.W., Nitao, J.J., Blair, S.C., and Morris, J.P., CO_2 reservoirs: are they natural analogs to engineered geologic storage sites? Special Session on Geological Sequestration of CO_2, AAPG Annual Meeting, Salt Lake City, UT, May 11-14, 2003
- Johnson, J.W., Nitao, J.J., and Morris, J.P., Reactive transport modeling of long-term cap rock integrity during CO_2 injection for EOR or saline-aquifer storage: Second National Conference on Carbon Sequestration, Alexandria, VA, May 5-8, 2003
- Johnson, J.W., Nitao, J.J., Blair, S.C., and Morris, J.P., Reactive transport modeling of geohazards associated with offshore CO_2 injection for EOR and geologic sequestration: Special Session on Geohazards (Fred Aminzadeh, organizer), Offshore Technology Conference 2003, Houston, TX, May 5-8, 2003
- Johnson, J.W., Nitao, J.J., Blair, S.C., and Morris, J.P., Reactive transport modeling to predict long-term cap-rock integrity, JIP CO_2 Capture Project Workshop: "Leveraging the SMV Family of Technology Providers", Santa Cruz, CA, Oct 21-23, 2002
- Johnson, J.W., Nitao, J.J., and Blair, S.C., Reactive transport modeling to predict long-term cap-rock integrity, JIP CO_2 Capture Project Workshop: "Building the SMV Family of Technology Providers", Potsdam, Germany, Oct 31-Nov 2, 2001
- The semiannual progress report for this project is in Appendix A under the same heading as this summary.

2.1.6 Early Detection and Remediation of Leakage from CO_2 Storage Projects

Principal Investigator: Sally M. Benson
Technology Provider: Lawrence Berkeley National Laboratory

Summary

A frequent issue brought up by environmental NGOs in discussion of CO_2 storage is the need for early detection and remediation of CO_2. As little research has been conducted on this topic, Lawrence Berkeley National Laboratory was contracted to scope the problem and identify novel approaches to addressing it. Although the study has been very recently contracted, CO_2 leakage scenarios and ideas for its early detection and remediation have been outlined. The project deliverable is a scoping paper that identifies:

- Monitoring approaches for early detection of leakage
- Remediation options that could be used to eliminate or manage risks after leakage has been detected
- Additional information and R&D that is needed to develop the remediation approaches identified.

The overarching goal of the proposed study is to begin to develop approaches that can be used to manage human health and environmental risks to an acceptable level in the event that a storage project leaks.

Detection and remediation of CO_2 leakage from CO_2 storage project is addressed by the following approach:

1. Calculate a range of leakage rates from prototypical storage projects, including those performing effectively and those leaking at unacceptable rates.
2. Identify and develop the major leakage scenarios that are most likely to occur in geologic storage projects (e.g. leakage up abandoned wells, leakage up undetected faults or fractures in the reservoir seal, etc.)
3. Identify the consequences of leakage in each of these scenarios (e.g. degradation of groundwater quality, human exposure to elevated CO_2 concentrations, etc.)
4. Identify monitoring approaches that could be used for early detection of leakage in each of the scenarios (e.g. seismic imaging, satellite or air-borne imaging, surface IR detectors, etc)
5. Survey and document remediation practices currently used in natural gas storage, oil and gas production, groundwater and vadose zone remediation, damn construction and maintenance and acid gas disposal.
6. Evaluate how and the extent to which existing remediation practices could be employed to remediate leakage in geologic storage projects.
7. Identify potential new approaches for remediation of geologic storage projects for scenarios where existing remediation approaches are not sufficient.
8. Identify additional knowledge or information needed to develop and build confidence in the effectiveness of new or improved remediation approaches.
9. Identify existing regulations that would be applicable to protecting human and ecosystem health at leaking geologic storage sites.

Work has begun on items 1-5.

A list of possible options for remediation of leaking CO_2 storage projects appears below (abbreviated from report).

a) *Ideas for vadose zone remediation*:
   i) Passive methods
   ii) Active methods
      (1) Soil gas extraction
      (2) Covers
      (3) Sprinkling/irrigation to dissolve CO_2 and move it downward

b) *Ideas for groundwater remediation*:
   i) Passive methods
      (1) Natural attenuation by dissolution, migration, and mineralization
   ii) Active methods
      (1) Gas phase pumping
      (2) Groundwater extraction to resolve plume
      (3) Single well dissolution system – inject CO_2 then water (WAG)
   iii) Methods to deal with other contamination due to dissolution of minerals by CO_2 (e.g., As, Pb)
      (1) Pump and treat with wells
      (2) Containment by managing hydraulic heads
   iv) Ideas for sealing faults in limited areas
      (1) Foam injection
      (2) Grout injection

c) *Ideas for managing surface fluxes*:
   i) Fans to dissipate hazardous concentration of CO_2 at night
   ii) Trenches – gravel-filled with covers to collect CO_2 from leaks such as faults or in the vadose zone

d) *Ideas for controlling leaks with in the storage reservoir*:
   i) Lower reservoir pressure
   ii) Extract CO_2 before it reaches the leakage path
   iii) Hydrofractures to access new areas of the reservoir away from areas of leakage

e) *Ideas for remediating leakage from abandoned wells*:
   i) Plug and abandon using techniques developed for oil and gas leaks

f) *Ideas for basement CO_2 remediation*
   i) Active or passive ventilation

g) *Ideas for remediation of CO_2 dissolved in deep lake*
   i) Controlled discharge of CO_2 through gas lift from depth (now used at Lake Nyos)

The completed project will detail numerous options for CO_2 leakage detection and remediation that will offer reassurance to NGOs, regulators and the public.

2.1.7 Impact of CO_2 Injection On Subsurface Microbes and Surface Ecosystems

Task - 4.1 - Understanding Geologic Storage
Technology Provider: Princeton University
Principal Investigator: T. C. Onstott

Highlights

- A literature survey to define the current understanding of the topic issues was completed.
- A draft final report was sent July 31, 2003.

Summary

Environmental assessment of subsurface CO_2 injection requires an understanding of impact on microbial communities both in the subsurface as well as surface. The project will provide an estimate of the present-day distribution and composition of deep microbial communities using literature review and compilation of current research. Furthermore, thermodynamic and kinetic modeling will project the outcome of CO_2 injection into these ecosystems. A variety of parameters including CO_2 concentration, carbonate versus clastic reservoirs, type of bacteria, and ground water salinity will be varied to observe the outcome in a range of scenarios covering the possible locations for CO_2 injection being considered by the CCP Consortium.

As of August 4, 2003 the project is nearing completion and the final version of the final report will be available soon.

Deliverables:

1) Review of literature – current understanding
2) Modeling outputs for CO_2 injection varying parameters such as rates of injection, total volumes injected, ambient temperature and pressure, and types of microbial biomass
3) Written report interpreting the findings.

Reports and Publications

- "Impact of CO_2 Injections on Deep Subsurface Microbial Ecosystems and Potential Ramifications for the Surface Biosphere," T.C. Onstott, Dept. of Geosciences, Princeton University, Draft Final Report, 4 August 2003.

2.2 Optimization

Task - 4.1 - Understanding Geologic Storage

The CCP-SMV optimization studies aim to realize efficiencies of CO_2 sequestration from EOR and EGCR, benefit from lessons learned from natural gas storage, and optimize storage to economic tradeoffs with capture technology.

The New Mexico Institute of Mining and Technology (Grigg) completed their study "Long-Term CO_2 Storage Using Petroleum Industry Experience" early in 2003. A survey of Permian Basin CO_2 EOR operators with projects dating back to the 1970s was taken to assess the type and rate of successes and failures. The data compiled reveals that whereas oil response timing has generally met expectations, there were substantial injectivity, CO_2 breakthrough, and scaling / corrosion problems. The variety of remediation attempts have been pursued to address problems is documented. The operators identified sweep/profile/conformance, productivity / injectivity, monitoring and prediction / economics as recommended research areas. Although monitoring of these operations has not been extensively applied, there is no evidence for large-scale leakage. The principal investigator's experience was that the industry possesses the technology needed to efficiently produce, transport and inject / recycle CO_2 on a large scale and that there is no records of a fatality associated with such operations.

"Use of Depleted Gas and Gas Condensate Reservoirs for the Geologic Storage of CO_2", conducted by Texas Tech University (Frailey /Lawal) uses laboratory measurements of the physical properties of CO_2 / hydrocarbon mixtures to predict their phase behavior in depleted gas-condensate reservoirs. From the resultant data, a material balance model has been developed to determine how much CO_2 can be stored in gases (dry, wet and retrograde). The capacity for CO_2 storage in reservoirs of varying gas and condensate content will be estimated. The suitability of reservoirs for CO_2 storage versus the potential of enhanced gas-condensate production with CO_2 storage will be possible using software developed for this study.

Reinertsen Engineering, with IFE as subcontractor, has evaluated existing pipeline transportation and is developing recommendations for optimizing CO_2 transportation. Reports have been issued on 1) dehydration, compression and transportation and 2) water solubility in CO_2 with calculation models and experiments to justify models.

Tieline Technology has completed the "Screening Tool for MMP / MME Evaluation". This software is used to predict minimum miscibility pressure and enrichment for injection gas (e.g., CO_2) into oil or mixed gas reservoirs. The Windows-based tool predicts phase behavior and the conditions for which multi-contact miscibility will develop when a gas is injected into reservoir oil. Once the fluid system is specified, PT- flash, bubble/dew point, phase envelope and MMP (including an indicator for sensitivity towards numerical dispersion if finite difference compositional simulation) are calculated and a conceptual slim-tube simulator, swelling test and MME simulation tool are made available.

The "Gas Storage Technology Applicability to CO_2 Sequestration" study by GTI (Perry) reviews gas storage technologies applicability to field integrity, monitoring and mitigation. A survey was sent out to Canadian and European operators to analyze successes and difficulties in natural gas storage. Specific problems, particularly those related to leakage, can be prevented by proper reservoir selection and monitored / mitigated using a variety of techniques. These experiences are relevant to CO_2 sequestration, but specific differences are anticipated given the distinct physical and chemical properties of CO_2 and natural gas. The safety record of the gas storage industry has been remarkable (6 reported gas migration incidents from ~600 storage fields over ~90 years).

The University of Texas (Pope) study "CO_2 Sequestration Modeling" uses a compositional reservoir simulator to quantify physical and chemical behavior phenomena associated with CO_2 sequestration in aquifers. The focus is on the effect of brine density changes and geochemical reactions associated with CO_2 injection. These processes might reduce leakage by CO_2 solubility trapping and formation of carbonate minerals (respectively). A base-case model that tests the sensitivity of permeability (mean, vertical, and horizontal), residual gas saturation, salinity and temperature shows that CO_2 storage capacity is strongly influenced by residual gas saturation.

Two newly contracted studies involve CO_2 Impurities "Tradeoffs", i.e., optimization of cost savings from capture of less than pure CO_2 (i.e. for example varying concentrations of reactive SOx and NOx) and the effects of injecting such a gases into a reservoir. The "surface" study, conducted by Battelle Memorial Institute (Gupta), examines possible untoward effects of CO_2 impurities on absorption and regeneration performance of amine and other solvents used to separate CO_2 from waste gas streams. Possible difficulties and their solution on materials used in pipelines, compressors, etc will be documented from the literature. The "subsurface" study conducted by the University of Texas (Bryant) will simulate the effects of these impurities on phase behavior, mobility ratio, WAG ratio, well productivity and spacing for EOR operations.

The optimization studies introduce several key lessons on efficiency and risk reduction that could make CO_2 sequestration economically feasible, effective and safe. Future research should focus on likely synergies gained from integration of results using realistic scenarios.

2.2.1 Depleted Gas and Gas Condensate Reservoirs for the Geologic Storage of CO_2

Task - 4.1 - Understanding Geologic Storage
Principal Investigator: Scott Frailey; Technology Provider: Texas Tech University

Highlights

- The analyses of results show that irrespective of the CO_2/hydrocarbon gas mixture's reservoir composition, dry and wet gas reservoirs remain as a vapor phase in the reservoir as well as at surface conditions, thereby showing no phase change in these reservoirs due to CO_2 storage. The same analysis is not yet completed for retrograde gas condensate reservoirs.
- The analysis of results shows that a developed Material Balance Model can provide estimates of CO_2 storage in gas reservoirs.

Summary

This research project is aimed at using laboratory measurement of the physical properties of carbon dioxide-hydrocarbon gas mixtures and reservoir simulation to investigate the phase behavior to be encountered by using depleted gas reservoirs for CO_2 storage.

To quantify the volume of sequestered CO_2, enhanced gas recovery (EGR) and enhanced condensate recovery (ECR), a material balance model (MBE) has been developed to determine how much CO_2 that can be stored in the respective dry gas, wet gas and retrograde gas reservoirs. This material balance model is currently being analyzed to include fundamental fluid and petrophysical properties of gas reservoirs.

The purpose of this project is to investigate the use of a depleted gas reservoir for the geologic storage of CO_2. Furthermore, a benefit may exist for the recovery of hydrocarbon gas and condensate that formed in the reservoir due to depletion below the dew point of the gas. The idea is to identify the geologic storage of CO_2 in terms of Mscf (or lbs) per acre-foot of reservoir formation as a function of initial pressure, reservoir temperature, hydrocarbon gas composition, water, and oil saturation. The three main objectives of the project are as follows:

- Study the feasibility of geologic storage of CO_2 in depleted or abandoned gas reservoirs.
- Determine EGR and EOR benefits of geologic CO_2 storage in dry gas, wet gas, and retrograde reservoirs.
- Develop guidelines for selecting optimal CO_2 storage reservoir candidates.

The methodology used towards proving a reliable and resourceful means of validating the use of depleted gas reservoirs for CO_2 storage follows:

- Collect group of candidate gas reservoirs.
- Classify gases as dry, wet, or retrograde based on TTU gas identification chart.
- Estimate CO_2 storage using TTU charts developed as CO_2 storage (MMscf) vs. *CO_2 Sequestration Parameter* (CSP, yet-to-be-determined) for each of the three gas types. (*Reservoir-Variable* includes rock and fluid properties specific to a candidate gas reservoir.)
- Estimate gas and condensate recovery using TTU charts developed as gas and condensate recovery (MMscf and Mstb) vs. CO_2 storage (from TTU Chart) and *CSP*.

The continued development of the CO_2 sequestration parameter (CSP) to be used to determine sequestered CO_2 volume (SCV), EGR and ECR is based on a novel combination of reservoir engineering fundamental equations, that is, P/Z plot, volumetrics, and diffusion-dispersion term for the porous media. Since mixing between the injected CO_2 and reservoir gas is influenced by macroscopic dispersion in the pores of the porous medium and dispersion is affected by permeability and viscosity, it is possible to draw the inference that permeability and viscosity have been acknowledged in the CSP. Therefore, CSP can be expressed in term of reservoir bulk volume, porosity, permeability, viscosity, gas formation volume factor, and diffusion-dispersion factor, that is, CSP can be symbolically represented as

$$CSP = f\ (B_g, V_B, k, \mu, \phi, K_d).$$

The highlight of this analysis is that CSP can be used to group compositional reservoir simulation results into a family of curves that can subsequently be used to predict the volume of sequestered CO_2 in a depleted gas reservoir.

The results of the laboratory experiments will be incorporated into the phase behavior software to create PVT data for use in the compositional and black-oil reservoir simulation. In order to correlate the ultimate sequestered CO_2 volume (USCV) with the CSP, multiple data sets from controlled reservoir examples for each of the three gas types are required to develop a usable correlation. The only controlled reservoir examples are via reservoir simulation models. Consequently, data sets will be synthetically generated using the compositional reservoir models. Using a representative range of the CSP parameter as input into the compositional reservoir simulation models, estimates of the sequestered CO_2 volume will be made. The final result will be CSV versus CSP for each gas type.

Likewise, to develop a correlation between SCV and the CSP to EGR and ECR, the same compositional model results used to the CSV vs. CSP graphs will be used to correlate EGR/ECR with CSP. The final result will be EGR and ECR vs. CSP for a family of SCV curves. Methodically, the gas type, reservoir fluid and rock properties, and the initial sequestration pressure are used to calculate the CSP. CSV is graphically estimated based on CSP. EGR and ECR are estimated based on CSV and CSP for a specific gas type.

To attempt a simplification of the final correlations of CSV vs. CSP and EGR/ECR vs. CSP for a family of SCV curves, black oil reservoir models will be used to simulate the compositional behavior identified with the compositional models. The compositional reservoir simulation provides the compositional benefits of CO_2 storage and also investigates the feasibility of a benefit of CO_2 storage that may enhance gas production and re-vaporize condensate deposited in the reservoir. The highlight of the simulation results is the development of guidelines for selecting optimal CO_2 reservoir candidates in terms of USCV, EGR and ECR. Conclusion

This research focuses on using laboratory investigation and computer simulation to analyze phase behavior and enhanced gas and condensate recovery by CO_2 storage in depleted gas reservoirs. The laboratory measured CO_2 compressibility factor (or Z-factor) is much lower than hydrocarbon gas mixtures at the specified temperatures and pressures. Therefore, that offers the opportunity to store larger surface volumes of CO_2 than hydrocarbon gases. Five times the storage is possible depending on pressure, temperature and hydrocarbon gas composition.

Reports and Publications

- Sobers, L. E., "Phase Behavior of CO_2 Sequestration in Depleted Gas Reservoirs," MS Thesis, Department of Petroleum Engineering, Texas Tech University, Lubbock, Texas (August 2003).
- The semiannual progress report for this project is in Appendix A under the same heading as this summary.

2.2.2 Screening Tool for CO_2 Miscibility Determination

Task - 4.1 - Understanding Geologic Storage
Principal Investigator: Erling Stenby
Technology Provider: Tie-Line Technology

Highlights

- This project has been completed and the final report delivered.

Summary

The result of the project is a software product that can be used to predict the Minimum Miscibility Pressure (MMP) for an injection gas - e.g. CO_2 - in a reservoir oil. Also it can be used to calculate the effect on the MMP of mixing two gases. Furthermore a dispersion free, semi analytical, one-dimensional compositional simulator was made available that is useful for prediction of the composition of the gas phase that will produced during the gas injection process. The simulation tool will be of significant importance in evaluation of CO_2 injection into oil reservoirs. A favorable license for the software will be available to the CCP partners.

The product is a Windows based tool for prediction of phase behavior and the conditions for which multicontact miscibility will develop when a gas is injected into a reservoir oil. The user must specify the critical properties of the reservoir fluid in question. When the fluid system is specified, several tasks are available for the reservoir engineer. These are a PT-flash, bubble/dew point calculation, phase envelope, MMP calculation including indicator for sensitivity towards numerical dispersion if finite difference compositional simulation, a conceptual slimtube simulator, swelling test and a MME simulation tool.

Reports and Publications

- No formal reports or presentations were made during the reporting period.

2.2.3 Reservoir Simulation of CO_2 Storage

Task - 4.5 - Risk Assessment and Mitigation Options
Technology Provider: University of Texas
Principal Investigator: Gary Pope

Summary:

The general goal of this proposed research at the University of Texas Austin is to use compositional reservoir simulation to better understand and quantify the chemical and physical phenomena associated with the sequestration of CO_2 in aquifers. More particularly, the group will quantitatively assess:

- Effect of common aquifer minerals (calcite, kaolinite, siderite, anorthite) on how much of the injected CO_2 can be stored as a solid carbonates. Relative contribution of the CO_2 in solid minerals compared to how much of the CO_2 remains in the gas and brine phases after long periods of storage (up to 1000 years).

- Effect of the increase in brine density due to the dissolved CO_2 (about 3%) and whether this density increase is large enough for it to be feasible to store all of the CO_2 in the brine and/or solid phases to mitigate at least some of the geological issues associated with CO_2 escape from the aquifer via faults, fractures or boreholes.

- Effects of well injectivity associated with injected composition, brine composition, aquifer heterogeneity and well skin and completion.

- Effects of relative permeability hysteresis and in particular the effect of trapped gas saturation on the transport of the supercritical CO_2.

A preliminary simulation study has been completed in the Center for Petroleum and Geosystems Engineering using the simulator UTCOMP. In a study by Vikas supported by DOE NETL, factors such as the effect of salinity were evaluated. After a careful effort to calibrate the physical property models in the simulator, a series of simulations were completed with aquifer storage times of 1000 years. However, mineral reactions were not modeled in this study.

Both the UTCOMP simulator and CMG's GEM simulator will be used in the proposed study. The UTCOMP simulator has the advantage that the source code can quickly and easily be modified to add new reactions, improved physical property models and the like. The GEM simulator has the advantage in terms of modeling complex geological features and could be used for large simulations up to one million grid blocks. GEM already has several of the key geochemical reactions pertinent to CO_2 sequestration in aquifers. Simple kinetic expressions will be added to the UTCOMP code and comparisons made between the two simulators as a preliminary step.

Reports and Publications:

- No formal reports or presentations were made during the reporting period.
- The semiannual progress report for this project is in Appendix A under the same heading as this summary.

2.2.4 CO_2 Impurities Tradeoff – Surface (SOx/NOx) Impurities Study)

Principal Investigator: Gupta
Technology Provider: Battelle Memorial Institute

Highlights

- Contract was executed July 23, 2003.

Summary

Gas impurities, such as SOx and NOx, have the potential for interacting unfavorably with the absorption and regeneration characteristics of amine and other solvents used to separate CO_2.

Battelle will assess the issues-related impact of impurities in CO_2 streams on above ground processing systems through three activities:

- Study into the effects of SOx and NOx on a few selected amines that are commonly used by the separation industry.
- Review the literature on compressed gases to determine the corrosivity of various pipeline and coating materials for Sox and NOx species with moisture present.
- Evaluate the phase behavior of multi-component gas-mixtures on multi-stage compressors.

The research will be limited to compilation of information in existing literature. Preliminary calculations may be performed.

A closeout report is planned by September 15th, 2003.

Reports and Publications

- No formal reports or presentations were made during the reporting period.
- The semiannual progress report for this project is in Appendix A under the same heading as this summary.

2.2.5 CO_2 Impurities Tradeoff – Subsurface

Technology Provider: University of Texas
Principal Investigator: Bryant

Highlights

- Contract was executed July 1st, 2003.
- Work to date has focused on a literature review to determine whether impurities might adversely affect enhanced oil recovery processes.
- The report identifies correlations of MMP with solvent composition that should allow fairly accurate estimates of the tradeoff between oil recovery vs. the cost of impurity removal.

Summary

CO_2 has been used as an enhanced oil recovery agent since the early 1970s and research on this technology predates that by nearly 20 years. Since that time, more than 50 CO_2 floods have conducted, primarily in West Texas, with a corresponding accumulation of field experience and production data. There has also grown a large technology base for the process, which we exploit in this work.

This project has two goals:

- To examine with a mathematical simulator the potential effect of highly reactive impurities (SOx, NOx) on well injectivity during large-scale CO_2 sequestration; and
- To review the literature to determine whether impurities might adversely affect enhanced oil recovery processes. Work to date has focused on the second goal.

The current progress report summarizes the literature on minimum miscibility pressure (MMP), thought to be one of the primary determinants to the success of an oil-recovering CO_2 flood. The report identifies correlations of MMP with solvent composition that should allow fairly accurate estimates of the tradeoff between oil recovery vs. the cost of impurity removal.

MMP is only one of the factors that determine the efficiency of a CO_2 flood. Other factors include mobility ratio, WAG (water-alternating-gas) ratio, well productivity as well as several reservoir-specific quantities such as heterogeneity and well spacing. These will be addressed in a subsequent report.

Closeout report is planned for September 15th.

Reports and Publications

- No formal reports or presentations were made during the reporting period.
- The semiannual progress report for this project is in Appendix A under the same heading as this summary.

2.3 Integrity

Task - 4.1 - Understanding Geologic Storage
Task - 4.4 – Measurement and Verification

The portfolio of CCP-SMV "integrity" projects address a broad range of issues relating to strengths and weaknesses of natural and engineered systems for CO_2 storage. Prototypical competent and incompetent venues for CO_2 storage are characterized to identify flaws and strengths. Reservoir and cap-rock capacity for resisting deterioration caused by CO_2 storage are addressed experimentally. Likely, the most vulnerable element in CO_2 storage, are existing wells and associated disrupted cap rock. These issues are being assessed experimentally and from an improved materials and protocols viewpoint.

"Evaluation of Natural CO_2 Charged Systems as Analogs for Geologic Sequestration" by Utah State University (Evans) examines a prototypical leaky, or incompetent reservoir for CO_2 sequestration, a natural geyser. A synthesis of the geology (structure and stratigraphy), hydrology and geochemistry is used to construct a detailed scenario for CO_2 origin, subsurface migration and leakage. Water associated with the geysers was found to be of meteoric origin based on oxygen and deuterium isotopes. The CO_2 emanating from the geysers is thought to originate from clay-carbonate or thermal decarbonation reactions. A case was made for isotopic equilibrium among carbonate species present minerals, water and gas (once corrections were made for fractionation) suggesting prolonged water-rock interactions and a lack of an extraneous source for CO_2 such as from mantle exhalations. The favored scenario for the origin and movement of CO_2 in this system: 1) meteoric water descends to >1.0 km where it is heated and reacts with the host rock to release CO_2, 2) CO_2 charged water moves laterally beneath clay seals and vertically up fault systems, 3) some CO_2 exsolves from the water at shallower depths and moves to the surface episodically with fault seal failure. Ancient and recent travertine deposits suggest that this process has been active since the early Tertiary and that despite extensive mineralization the system is not self-sealing.

The ARI (Stevens) study "Natural CO_2 Field Analogs for Geologic Sequestration" characterized geologic features of three natural CO_2 accumulations (McElmo Dome, Jackson Dome and St. Johns Field) that result in "successful" long-term storage of CO_2. The study also identifies procedures that have permitted safe and effective handling of these resources. The data gathering is complete and geologic; reservoir and production analyses and synthesis thereof are nearly complete. The results of the study should dispel fears that geologic sequestration of CO_2 is not "natural" or and cannot be accomplished without acceptable risk. Lessons learned will improve cost effectiveness, safety and performance of CO_2 handling and storage management.

The GFZ-Potsdam (Borm) study "Influence of CO_2 Injection on the Physical Properties of Reservoir and Cap Rocks" is focused on experimental exposure of rocks to CO_2 at reservoir pressures and temperatures. Post-experiment, physical properties (seismic velocities, ultrasonic frequency range, electrical conductivity, quasi-static Young's modulus and transport properties) of the rocks were measured to assess how CO_2 affects their mechanical strength. Additional petrographic and fluid chemistry analyses document mineral precipitation and dissolution. To date, several experiments have been run and the resultant data compiled. Preliminary analysis suggests that seismic wave speeds follow trends predicted by the Gassmann model for fluid substitution problems. The Vp is reduced by several percent with supercritical CO_2 present whereas Vs is essentially unchanged. Flooding with non-supercritical CO_2 changes velocity characteristics permanently, suggesting chemical mobilization. The nature and extent of chemical transformations is now under investigation and autoclave experiments to document reaction kinetics has begun.

SINTEF's (Lindeberg) study of "The Long-Term Sealing Capacity of Cemented Petroleum Wells in a CO_2 Storage Project" has documented well cement and steel dissolution rates and mechanisms upon exposure to stagnant and flowing CO_2 at reservoir pressure and temperature. Recognizing that not only well materials but the adjacent cap rock is vulnerable to failure during long-term CO_2 storage, SINTEF continues work on identifying well materials and well completion techniques that can reduce the risk of CO_2 leakage.

The newly contracted "A Study of the Geomechanical Effects of CO_2 Storage with Emphasis in the Effect of Stress on Seal Integrity" by APCRC (Rigg) is designed to predict stress effects on reservoirs and seals resulting from CO_2 injection and recommend optimization of leak monitoring and prediction technology.

Given that well and cap-rock (particularly adjacent to the well bore) is generally recognized as the most vulnerable element in CO_2 storage, future work should be directed towards experiments and simulations to quantify the risk and the development of preventative and remediative solutions.

2.3.1 Evaluation of Natural CO_2 Charged Systems for CO_2 Sequestration

Task - 4.1 - Understanding Geologic Storage
Principal Investigator: James Evans
Technology Provider: Utah State University

Highlights

- An integrated assessment of the geology, hydrology and geochemistry of natural CO_2 geysers on the Colorado Plateau of Utah aimed at documenting features that make geologic systems prone to CO_2 leakage is underway.
- The geological setting of the CO_2 geysers is documented in detail. Considerable work was done in collecting and analyzing appropriate samples to infer the origin of groundwater and CO_2 emanating from the geysers.
- The CO_2 present in the geysers is determined to originate from clay-silicate or thermal decarbonation reactions at elevated temperature. Carbonate species in three phases (minerals, water gas) were found to be in isotopic equilibrium, suggesting thorough water rock interaction.
- Fault sealing by clay gouge or calcite precipitation was evidently ineffective. Movement of these deep-soled faults, is thought to have occurred repeatedly since the early Tertiary, allowing large quantities of CO_2 to escape.

Summary

The Evaluation of Natural CO_2 Charged Systems for CO_2 Sequestration project is preparing a case study of 'failed' natural CO_2 storage sites and will produce a 3D model of the origin, storage and release of CO_2. Several natural CO_2 leaks have been identified in Utah, including one, a geyser that blows twice daily. Understanding why some CO_2 systems leak and others don't is a 'critical success factor' for CO_2 storage. The group has evaluated literature reservoir flow maps and performed geologic mapping and synthesis for these natural analogs. Geochemical analysis of the water, gas and oil and minerals associated with these analogues has been made and a model framework put in place. Modeling studies are underway to address flow and sensitivity issues. The design for an injection experiment will be completed as part of the final product.

Deep sequestration of CO_2 in underground reservoirs may provide the most cost-effective, technically feasible, and politically acceptable short-term method to limit CO_2 emissions, especially where large CO_2 point sources exist and a suitable underground reservoir is nearby. With increasing interest in the possibility of subsurface CO_2 sequestration it is important to assess the feasibility of different sequestration options in natural CO_2 reservoirs. Issues that must be addressed at specific sites include:

- Influence of fine-scale variations in permeability caused by faulting, fracturing or facies variation on CO_2 injectivity near the well bore and the ultimate migration of CO_2 throughout the prospective reservoir system,
- Reasons for failure of CO_2-charged systems and the rates / volumes of CO_2 loss in the short and long term,
- Ability of various water rock interactions (function of temperature, pressure and salinity) found in separate, neighboring reservoirs to aid identification of a preferred storage option.

The present study addresses these issues by detailed characterization of the structural, stratigraphic and hydro-chemical system of a natural, leaking (geyser) CO_2 reservoir. This work could be used to identify

elements of reservoir systems that make them prone to leaking and thus quantify and establish risk of CO_2 storage options. Effective use of geologic sites for CO_2 sequestration requires careful evaluation of system geology (permeable beds, faults, seals) to ensure that leakage rates are acceptable. The objective of this study is to evaluate "leaky", or incompetent CO_2-charged systems to document features that are inconsistent with long-term geologic CO_2 sequestration.

In addition to some large natural CO_2 accumulations, numerous CO_2 charged geysers have been identified on the Colorado Plateau. This study focuses on geysers associated with the Little Grand and Salt Wash faults in East-central Utah, where the Colorado Plateau adjoins with the Paradox Basin. These high angle, anastomosing fault complexes crosscut sandstones, siltstones and shales with evidence of clay-rich gouge and calcite precipitation. As is evident from past (travertines) and present geyser activity, fault sealing has not been effective.

An extensive sampling program that includes carbonate minerals, water and gas was undertaken in this study. Field sampling appears to have been well planned and rigorously conducted. Safeguards were in place to avoid atmospheric contamination and preserve samples for laboratory analysis. The analytical plan and execution was appropriate to achieve the interpretive goals of the study. New insights into collection and analytical protocols of these physicochemically unstable water and gas samples are an important feature of this study.

Analyses of gases, waters and minerals are used to infer the origin of each and to develop a comprehensive carbonate system history for the system. He isotopic analysis suggests a crustal, as opposed mantle/magmatic origin for the gas. This, however, assumes that crustal He was always associated with the system and that mantle/magmatic He that might once have been associated with the system was not lost. The conclusion of crustal He origin seems likely given that the geyser waters are not hydrothermal and volcanic intrusions are not known in the area. The $\delta^{13}C$ values for CO_2, TDC and calcite were determined and an effort was made to assess their respective origins. The $\delta^{13}C$ values for the carbonate species averaged -6.6‰ (gas), +0.6‰ (TDC) and +5.6‰ (calcite). Considerable effort was made to determine if the carbonate system was in equilibrium and therefore compatible with a similar origin. Taking into account fractionation resulting from natural rock-water-gas interactions and sampling, corrections of measured values were made. The conclusion was that the carbonate system is indeed equilibrium. The procedure used and the presentation thereof, however, is in need of more clarity before this conclusion should be accepted.

The origin of CO_2 in the study area was tested against three possibilities:

1) Mantle or magmatic emanations,
2) Degradation of organic matter,
3) diagenetic reactions involving clay (siliceous) and carbonate rock,
4) thermal decarbonation of carbonate rocks by metamorphic processes.

The isotopic value of the CO_2 (average = -6.6‰) is compatible with all of the listed origins although the mantle / magmatic explanation is thought unlikely given the He isotopic results. The authors propose clay-carbonate diagenesis as the likely source of the CO_2 although an equally plausible origin might be hydrolysis of carbonate rocks or cements at moderately elevated temperatures (although it is suggested from solute chemistry that "simple" calcite dissolution alone is not occurring). Supporting this is the likely meteoric origin of the host water as evidenced by H and O stable isotope results. A bacterial (anaerobic fermentation) possibility is not considered although uncorrected carbon isotope data from the TDC and precipitated calcite might favor this explanation. Release of CO_2 from organic diagenesis is also a possibility as a minor contributor to the total CO_2.

The favored scenario for the origin, subsurface movement and leakage to the surface of CO_2 in the east-central Utah geysers reads:

1) Meteoric water descends to depth (1.0-1.5 km) where it is heated and interacts with the host rock to incorporate dissolved carbonate species,
2) CO_2 charged water moves laterally underneath fine-grained seals and vertically up through fault complexes,
3) Some CO_2 exolves from solution at shallower depths and moves to the surface CO_2 charged water in an episodic fashion afforded by fault movement or breaching of vein precipitates. It is evident that the faults are not self-sealing. The longevity of this system is evidenced in the presence of extensive recent and ancient travertine deposits in the area.

The remainder of the project will focus on construction of a 3D geologic model, including flow paths, from which there will be an opportunity to history match the release of CO_2-charged water from the system. The numerical model might be used to benchmark with other numerical models and test the integrity of features necessary for long-term CO_2 storage in geologic systems.

2.3.2 Long Term Sealing Capacity Of Cemented Petroleum Wells

Principal Investigator: Erik Lindeberg
Technology Provider: SINTEF
(Task - 4.1 - Understanding Geologic Storage)

Highlights

- Project is complete. Technical SINTEF Report no. 54.5232.00/01/03 entitled "Report January 2003: The long term sealing capacity of cemented petroleum wells in a CO_2 storage project" was submitted and accepted.

Summary

The objective of this study was to estimate the risk of CO_2 leakage from abandoned petroleum wells and to make recommendations for well plugging and treatment prior to field abandonment. This study aimed to verify the integrity of well materials to avoid leakage of wells that penetrate sealing caprock for CO_2 storage. SINTEF was the technology provider for this work that includes the long-term degradation/erosion of steel and cement in the subsurface environment during and after CO_2 injection. Studies were conducted on the long-term corrosion of cement and steel in a CO_2/brine environment and the cross effects of steel corrosion in cement. The erosion of cement in flowing and stagnant CO_2/brine at various temperatures and pressures in the presence and absence of steel were assessed. The final product included mechanisms and rates of steel corrosion/cement corrosion and the contact effects at various temperatures and pressures useful for predicting integrity over thousands of years. The final report considered remedies to avoid leakage such as special cementing and produce some recommendations for well plugging and abandonment.

The advantage of storing CO_2 in abandoned oil and gas fields is that the geological formation has already demonstrated long-term sealing capacity. However the seal integrity is altered when it is penetrated by production and exploration wells and the wells represent a potential escape path for stored CO_2. Corrosion of steel and reaction between CO_2-rich brine and cement must be considered and related to creation of leak paths.

Reports and Publications

- Mid-term report June 2002: The Long Term Sealing Capacity of Cemented Petroleum Wells in a CO_2 Storage Project. Presented at the Santa Cruz, CA, workshop October 21-23, 2002.
- Presentation: SMV Santa Cruz, CA, Workshop October 21-23, 2002: Well materials, leakage and experiments.
- SINTEF Report no. 54.5232.00/01/03 entitled "Report January 2003: The long term sealing capacity of cemented petroleum wells in a CO_2 storage project".
- The semiannual progress report for this project is in Appendix A under the same heading as this summary.

2.3.3 Geomechanical Effects of CO_2 Storage With Emphasis on the Effects of Stress on Seal Integrity

Technology Provider: **APCRC**
Principal Investigator: **Andy Rigg, Juergen Streit, Milovan Urosevic, D. Sherlock**

Highlights

- The contract for this project has been executed
- Work is underway.

Summary

The goal of the project is to produce a report that documents the predicted stress effects on, and responses by, both reservoirs and seals resulting from storage of CO_2 in geological formations. The main objectives are to study the expected geomechanical responses of both reservoirs and seals, and the optimum technologies for verification of geomechanical responses, and in particular technologies for early leak detection.

Deliverables will be:

1 Brief discussion of CO_2 storage processes, concentrating on the likely changes in stress fields in the reservoir and the seal.

2 Discussion of seal characterization especially relating to seal capacity measurement

3 Discussion of the factors controlling geomechanical changes which are predicted to occur, with a focus on likelihood of induced seismicity, fault reactivation and fault or fracture initiation, and measures to be taken to reduce likelihood.

4 Discussion of monitoring technologies available and the underlying changes in physical/chemical properties being measured, concentrating on those that appear most suitable to detect changes in stress in both the reservoir and seal, again with a focus on induced seismicity.

5 Review of technologies that appear suitable for early leak detection.

Reports and Publications

- None as yet.

2.4 Monitoring

Task - 4.4 - Measurement and Verification

2.4.1 Atmospheric CO_2 Monitoring Systems – A Critical Review of Available Techniques and Technology Gaps

Technology Provider: CalTech
Principal Investigator: Yongchun Tang & Patrick J. Shuler
Task - 4.4 - Measurement and Verification

Highlights

- Tang and Shuler have produced a report assessing the current state of the industry technology capabilities as regards CO_2 atmospheric monitoring.

Summary

The report considers detection methods ranging from personal monitors that might be worn to warn a project employee of very high local concentrations of carbon dioxide, to instruments mounted in satellites to detect over many square miles any subtle increases in CO_2 that might be associated with a leakage of the injected greenhouse gas back to surface.

The greatest challenge and probably most important application is the long-term, continuous measurement of CO_2 near ground level across the several square miles of a project area, and the immediate surrounding area. Options include

1) Remote sensing from satellites or aircraft,
2) Development of new open path instruments that can sample over significant distances, or
3) A large network of conventional fixed point detectors.

NASA indicates satellite surveys might be useful for a "global" view of CO_2 although they may be limited to two-dimensions (satellites do not sample at ground level, but over the entire air column, from the surface to the stratosphere). Aircraft surveys may be an efficient means to collect data near ground level, but this is only practical in an infrequent basis.

Novel instruments located on the ground that are based on open path sampling appear to offer a good compromise. They could have the capability to detect increases of just a few percent of CO_2 from normal background, over a sample path of tens of meters, and, importantly, continuously and with unattended operation. Potentially, just a few such instruments could provide efficient long-term monitoring over a large area.

Many different commercial fixed-point units suitable for networking are available, but this is probably an impractical approach to monitor more than a small area. These detectors are better suited for deployment to monitor sensitive, high-risk points of leakage. Infrared spectroscopy detection based methods are the most common technical approach for CO_2 measurement in ambient air.

The report also discusses other novel approaches to carbon dioxide monitoring. For example, one technology development in progress is the real-time measurement of carbon and oxygen isotopes via laser spectroscopy. This technique could aid in pinpointing the source of the measured CO_2. Another example is the efforts by NASA to use satellite data to determine the changes in the biomass (e.g. changes in forest cover) over large areas. These observations provide a method to monitor carbon sinks over a wide area,

and also are related at least indirectly to changes in greenhouse gas concentrations. CCP is sponsoring at LLNL a similar approach where remote sensing is used to monitor changes in local fauna as indicators of elevated CO_2 concentrations.

Recommended Further Studies and Activities

1. Development should be encouraged for a long, open-path laser spectrometer instrument to measure CO_2 in the ambient air. Potentially, a single such laser device positioned near ground level could cover a radius of several square miles. Such a device would have the distinct advantages of continuous monitoring, accuracy to within a couple of percent, and remote and unattended operation.

2. Further discussions are encouraged with NASA with regards to their research activities and plans for monitoring greenhouse gases. NASA has several separate research efforts that bear directly or indirectly on the CO_2 monitoring requirements for CCP.

3. Track future developments in laser/detection technology because improvements in this hardware can aid in creating more cost-effective CO_2 measurement devices.

4. Use ongoing CO_2 sequestration project sites such as at Weyburn Field as test beds to evaluate and develop further CO_2 monitoring concepts.

Track further developments in laser spectroscopy technology that can measure in real time carbon and oxygen isotopes; such data could serve as tracers for the fate of transported or injected CO_2. This approach would complement the ongoing CCP supported project that is evaluating isotopic analysis of noble gases as a tracer for gas migration in sequestration projects.

Reports and Publications

- No formal reports or presentations were made during the reporting period.
- The semiannual progress report for this project is in Appendix A under the same heading as this summary.

2.4.2 Novel Geophysical Techniques To Monitor CO_2 Movement

Task - 4.4 - Measurement and Verification
Principal Investigator: Mike Hoversten
Technology Provider: LBNL

Highlights

- Seismic techniques, gravity measurements and streaming potential have been tested as monitoring techniques.
- This project is scheduled to complete by October 31, 2003.

Summary

A number of different geophysical techniques are considered in this project. Seismic, gravity, electromagnetic and streaming potential (SP) geophysical techniques are being considered as CO_2 monitoring tools in this study. To date, seismic, gravity and SP have been modeled and have been considered in the latest report. Numerical modeling has been done on flow simulations based on a proposed CO_2 sequestration project on the North Slope of Alaska (Schrader Bluff) as well as a project in South Texas (to be begun in fall 2003). The SP modeling done for the project is more limited than the other geophysical techniques because the SP modeling codes are restricted to steady state injection in 2D whereas all other geophysical modeling is three-dimensional. The SP part of the project has also involved laboratory measurements of fundamental properties of SP for CO_2 injection into sedimentary rocks.

The magnitude of the surface gravity response calculated for Schrader Bluff is approximately an order of magnitude above the gravimeter sensitivity, and therefore measurable in the field. However, the difference caused by CO_2 injection over a 5-year period is only about 0.5 μGal, which is in the noise level of the field survey (Hare, 1999). The decrease in the gravitational attraction of the reservoir is caused by increased CO_2 saturations reducing the bulk density of the reservoir. The spatial pattern of the change in the vertical gradient of gravity has a strong correlation with the change in reservoir pressure. Just as with the vertical component of gravity, the magnitude of the gradient signal measured in the field is above the gradiometer accuracy, but the difference between initial conditions and 5 years into CO_2 injection is very small. If the changes in dG_z/dz could be measured, due to advances in technology, it offers a potential tool for monitoring. In addition to surface gravity measurements, we have also modeled borehole gravity measurements. The difference in both the borehole vertical component of gravity and the borehole vertical gravity gradient (dG_z/dz) identifies the position of the reservoir. The sign of the change reflects the changes in the local densities caused by either water or CO_2 saturation changes.

The seismic amplitude associated with the reservoir interval in the Schrader Bluff model shows a large response to changes is water and CO_2 saturation produced by the simulated CO_2 sequestration. In addition, the AVO response of the reservoir reflections shows a significant change as sequestration proceeds. Both amplitude and AVO can be exploited to make quantitative estimates of saturation changes. Forward calculations using Zoeppritz equation for both 2005 and 2020 models support this argument. We have developed an AVO inversion technique for estimating saturations from AVO data that will be applied to the synthetic data set by the end of the project.

Hoversten et al. may be unduly pessimistic about the accuracy of future borehole gravimeters, and so the report's conclusions must be interpreted in the light of current gravimetric measurement accuracy.

Reports and Publications

- Hoversten, G., M., Gritto, R., Washbourne, J., Daley, T., M., 2003, Pressure and Fluid Saturation Prediction in a Multicomponent Reservoir, using Combined Seismic and Electromagnetic Imaging. Geophysics, (In Press Sept-Oct 2003). LNBL - 51281
- Hoversten. G. M., Gritto, R., Washbourne, J., Daley, T., ,"Non-seismic geophysics for CO_2 Sequestration Monitoring", 2002 SEG Workshop on CO_2 sequestration Oct. 10, 2002, SEG Annual Convention
- Hoversten. G. M., Gritto, R., Washbourne, J., Daley, T., "CO_2 gas/oil ratio prediction in a multi-component reservoir by combined seismic and electromagnetic imaging", 2002, LBNL report # 51408
- Hoversten, G. M., Myer, L., Daley, T., "Crosswell seismic and electromagnetic monitoring of CO_2 sequestration", 2002, GHGT-6 conference, Kyoto, Japan.

2.4.3 Optimum Monitoring Technology

Task - 4.4 - Measurement and Verification
Principal Investigator: Rob Arts
Technology Provider: TNO-NITG

Highlights

- The project was completed yearend 2002 and a final report was delivered.
- The study provides a comprehensive roadmap of potential monitoring technologies that may be useful in future projects.

Summary

The Optimum Monitoring Technology project completed by TNO-NITG reviews the benefits of currently available monitoring techniques and provides a best practice manual for CO_2 sequestration and monitoring. The present work was directed to the improvement of long-term monitoring & verification for sequestration of CO_2 in various geological media. The experience from other projects (SACS, RECOPOL, Coal and Gas Thermie B, NASCENT, Dutch NOVEM study) were used to set guidelines for an optimum monitoring strategy for the different geological options. Baseline measurements prior to CO_2 injection are needed so that sequestration induced changes can be observed. This implies that monitoring techniques must be selected at the earliest stage of each sequestration project to provide the "base case." This study gives "best practice" guidelines for such a selection by defining the key geological parameters and circumstances required for the different techniques and an estimation of the accuracy obtained.

The objectives of monitoring underground CO_2 storage are:

- To ensure the sustainability of the CO_2 reduction target and
- To ensure the safety requirements for subsurface activities during and after the operational phase

The first objective is focused on tariffs and legislation, whether the agreed quota as originally planned for CO_2 sequestration are met and maintained. The second objective is more important focusing on the safety issues of the storage site. The main risks as a consequence of underground CO_2 sequestration can be categorized as:

- Leakage to the surface or other geological formations with possible groundwater contamination or escape to the atmosphere as a consequence.
- Uplift due to injection of CO_2 or subsidence due to production or leakage of CO_2 can cause damage to constructions at the surface.

A secondary goal of monitoring is research and development regarding underground CO_2 sequestration. Gaining more understanding of the processes going on in the reservoir is important for the optimization of future storage sites.

CO_2 sequestration has to be monitored so that the operators and public will know that the CO_2 is not leaking to the surface (or overburden) where it is migrating in the reservoir. In this report a broad approach has been chosen taking into account as many monitoring techniques as possible. Globally three areas of investigation for monitoring can be identified:

- Reservoir integrity: Pressure, temperature, spreading and long-term fate of the CO_2.
- Seal integrity: Fractures, faults, wells, heterogeneous permeability.

- Migration pathways in the overburden and the atmosphere.

The first and especially the second are probably the most important areas in terms of an early warning system for possible leakage. In the ideal case one would expect to "see nothing" in the third area.

Monitoring techniques have been divided into 3 categories:

- Instrumentation in a well (monitoring well)
- Instrumentation at the (near) surface (surface geophysical methods)
- Sampling at the (near) surface measuring CO_2 concentrations (geochemical sampling techniques)

The final report describes the each of the available monitoring techniques and gives direction on which are likely to be successful in CO_2 storage applications.

Reports and Publications

- CO_2 Optimum Monitoring Methodology, R.J.Arts & P. L. A. Winthaegen, Netherlands Institute of Applied Geosciences TNO, Report NITG-02-229-B, 23 December 2002.

2.4.4 Hyperspectral Geobotanical Remote Sensing for CO_2 Storage Monitoring

Task - 4.4 - Measurement and Verification
Principal Investigator: William Pickles
Technology Provider: LLNL

Highlights

- Highly detailed maps of soil types, plant species, plant health, water conditions, and human activities were created. The results will be verified in a field trip to Rangely in August 2003. These maps establish an environmental and ecological baseline against which any future CO_2 leakage effects on the plants, soils, and water conditions can be detected and verified.
- Signatures that may be subtle hidden faults have been noted. If confirmed these faults might provide pathways for upward CO_2 migration if that occurred at any time during the future.

Summary

This project has the goal of providing a method of mapping for CO_2 leaks by the effects on the plants of excess soil CO_2 concentrations and for mapping hidden fault pathways for potential CO_2 leaks, over the entire region above an underground formation being injected with CO_2. The method uses airborne hyperspectral high-resolution imagery obtained through collaboration with a commercial hyperspectral imagery provider so that eventually ongoing surveillance of a field will be commercially available.

The experimental method can be summarized as:

1. Define area to be monitored including areas that are believed to be outside the expected CO_2 leakage perimeter.
2. Define flight lines along which images will be acquired.
3. Using GPS (Garmin 76 handheld with mapping) and digital cameras (Canon G2) visually record the soils, plants, minerals, waters, and manmade objects in the area.
4. After data acquisition, review the imagery and performs geo-rectification. Acquisition contractor carries out final post processing.
5. The imagery data set for all flight lines is post-processed and returned as in three files: Raw data, Data corrected for reflectance including atmospheric absorptions, and Geo-rectification control files.
6. Imagery is analyzed using the ENVI commercial computer software by the team from UCSC, LLNL, and HyVista Corp. Maps of plant species types, plant health within species types, soil types, soil conditions, water bodies, water contents such as algae or sediments, mineralogy of exposed formations, and manmade objects such as roads, buildings, playgrounds can be prepared.
7. Imagery is evaluated for abnormal observations of plant distribution, relative plant health patterns, altered mineral distributions, soil type distributions, soil moisture distributions, water, and water contents.
8. The research team verifies their observations with a field analysis. The analysis can be “fine-tuned” in the field to produce more accurate maps for analysis.

Reports and Publications

- No formal reports or presentations were made during the reporting period.
- The semiannual progress report for this project is in Appendix A under the same heading as this summary.

2.4.5 Long Term Monitoring And Verification Using Noble Gas Isotopes

Task - 4.4 - Measurement and Verification
Principal Investigator: Greg Nimz
Technology Provider: LLNL

Highlights

- Initiated noble gas isotopic analyses on samples obtained from the Mabee EOR field.
- Based on the initial Mabee analyses, the quantities of noble gas tracers required for an actual CO_2 storage setting were calculated. Cost estimates relative to total CO_2 storage costs and CO_2 "taxes" were derived.
- The distinct elemental and isotopic composition of the noble gases present in the injected CO_2 can be used as noble gas tracers of the EOR process. The 15 samples collected from the Mabee field show a good spread in CO_2 noble gas contributions in the recovered casing gas.
- Literature survey was completed to obtain satisfactory rock properties for incorporation into a NUFT-C model of gas transport through the shallow crust. This includes obtaining data on porosity-permeability relationships, mineralogy and lithological heterogeneity.
- Initial simulations of noble gas transport were produced. These form the basis of a noble gas monitoring strategy.
- This project is faced with major funding issues. Discussions are underway with the principal investigator to try and resolve the issues. Work scope reductions will likely be required.

Summary

The objective of this project is to develop the technological foundation for using noble gas isotopes to:

1) Create a mechanism for long-term monitoring of CO_2 storage sites;
2) Test EOR reservoirs for CO_2 leakage caused by production-related changes in caprock integrity (thereby screening for their suitability for long-term large volume CO_2 storage);
3) Screen brine aquifers or similar formations for suitability for CO_2 storage; and
4) Provide a mechanism for fingerprinting injected CO_2 so that the source and ownership of leaking or migrating CO_2 can be identified.

The project is comprised of three basic components:

- Collecting and analyzing noble gas isotopes accompanying both injected and recycled CO_2 at an operating Enhanced Oil Recovery (EOR) field in the Permian Basin of West Texas.
- Initiate a noble gas tracer test at an active EOR field. Injected CO_2 will be spiked with identifiable noble gas isotopes; recycled CO_2 will be monitored for recovery of spike signals. This and the previous component will provide a proof of principle and "debugging" of techniques for noble gas/CO_2 injection.
- Develop a NUFT-C computer model of noble gas tracers migrating upward through the crust from a leaking CO_2 storage site. This component will form the basis for the design of a monitoring strategy.

Activities during this reporting period included:

- Began compilation of geologic and hydrologic data relevant to the Permian basin (especially the Mabee EOR field) for the purpose of development of a NUFT-C prototype numerical model of noble gas migration in crustal media. This will form the basis of a monitoring strategy for CO_2 leakage.
- Initiated noble gas isotopic analyses on samples obtained from the Mabee EOR field.
- Analyses of neon and argon from samples of well casing gases from the Mabee EOR field, west Texas, were completed, and preliminary helium and xenon data were obtained.
- Based on the work at the Mabee EOR field. it is clear that the distinct elemental and isotopic composition of the noble gases present in the injected CO_2 can be used as noble gas tracers of the EOR process. The 15 samples collected from the Mabee field show a good spread in CO_2 noble gas contributions in the recovered casing gas. While the neon and argon components from the injected CO_2 give similar results, the signal at xenon (fission xenon - primarily 134Xe and 136Xe) appears to be depleted relative to neon and argon, possibly suggesting preferential partitioning of the xenon into a hydrocarbon liquid phase.
- Literature survey was completed to obtain satisfactory rock properties for incorporation into a NUFT-C model of gas transport through the shallow crust. This includes obtaining data on porosity-permeability relationships, mineralogy and lithological heterogeneity. Although the first model will incorporate a simplified stratigraphy, these data will provide the basis for constructing that first model in such a way as to allow expedient incorporation of heterogeneity in the second set of model runs.
- Initial simulations of noble gas transport were produced. These form the basis of a noble gas monitoring strategy.

Reports and Publications

- Nimz, G.J., Hudson, G.B., and Glassley, W.E., Noble gas isotopes for screening, verification, and monitoring at CO_2 storage sites, JIP CO_2 Capture Project Workshop: "Building the SMV Family of Technology Providers", Potsdam, Germany, Oct 31-Nov 2, 2001. (presentation)
- Nimz, G.J., Hudson, G.B., and Glassley, W.E., Noble gas isotopes for screening, verification, and monitoring at CO_2 storage sites, JIP CO_2 Capture Project Workshop: "Building the SMV Family of Technology Providers", Santa Cruz, California, Oct 21-23, 2002. (presentation)

2.4.6 Monitoring Geologic Sequestration with Satellite Radar Interferometry

Task 4.4 Measurement and Verification
Principal Investigator: Howard Zebker
Technology Provider: Stanford University

Highlights

- The applicability of satellite radar interferometry (InSAR) to detecting ground movement (deformation) due CO_2 injection (sequestration) was investigated. Deformation modeling was used to produce surface deformation maps that could be tested against InSAR sensitivity. The advantages of InSAR detection relative to tiltmeters and GPS are compared.

- Given ERS radar system parameters and allowing for atmospheric "noise", a sensor baseline was derived. InSAR resolution is expected to be in the 1 cm range (compared to tiltmeter < 0.1 rad, GPS < 1cm). Atmospheric effects may diminish this resolution by 10 mm.

Summary

This study investigated the theoretical resolution of satellite radar interferometry (InSAR) in detecting small ground movements induced by CO_2 injection into reservoirs. The advantages of this technology would include high spatial coverage (20 m postings over a large area), continuous data collection and ease of data collection. The approach is compared to the resolution of other technologies such as tiltmeters (<0.1 rad) and GPS (<1 cm). Influences that can diminish the resolution of the InSAR technique include atmospheric and topographic effects.

Using a model reservoir (2000 m depth, 4000 m radius, 100 m thickness, 6CPa shear modulus, 0.25 Poisson's Ratio, 20% porosity, 10 mD permeability, hydrostatic pore pressure and standard geothermal gradient) and injection protocol (supercritical CO_2, 12 months, constant 30kg/s) injection swelling (deformation) was modeled and mapped. An expected deformation detection of the InSAR method using the model reservoir and injection properties is thought to be ~ 1 cm. Modeling of noise due to atmospheric effects was calculated at 10 mm. Modeling of the topography influence was mentioned but no numerical figure was put forward.

The authors concluded that given the ERS radar system parameters a sensor baseline could be established. Differential InSAR can be used to detect small surface deformation signals due to CO_2 sequestration. Future work proposed identifying CO_2 sequestration or oil and gas reservoirs to test the InSAR data and inversion of InSAR measurements for pressure changes at depth.

This study was terminated at the 2002 SMV Meeting (Santa Cruz) with lack of progress. Resolution was considered insufficient to give meaningful measurements. The study was terminated in September 2002 due to high technical risk for deployment.

2.4.7 Measurement Techniques For the Detection of Leaks From Underground CO_2 Reservoirs: Evaluation and Summary of Capabilities

Task - 4.4 - Measurement and Verification
Technology Provider: Penn State University
Principal Investigators: K. J. Davis, J. C. Wyngaard

Highlights

The contract for this effort has now been signed.

Summary

The contract was recently executed. The work statement is reported here. Work is underway.

We shall evaluate techniques for measuring the flux of CO_2 from the earth's surface, focusing on the eddy-covariance technique and its potential application to monitoring underground CO_2 reservoirs. A report will be written based on a review of existing experimental and theoretical studies. The report shall include: the basic principles of the eddy-covariance technique for measuring turbulent fluxes in a micrometeorological environment; sensor-design criteria for application to CO_2 fluxes and mixing ratios measured in the atmosphere near the earth's surface; discussion of the merits of commercially available sensors and eddy-covariance system components; the use of the technique in horizontally homogeneous applications, such as over crop fields and forest canopies; the application of the eddy-covariance technique to isolated sources via the source "footprint" concept; discussion of our recent experience with the footprint technique in geothermal regions; possible complications of extending this technique to complex terrain; expected measurement precision and detection limits.

Reports and Publications

None to date due to brevity of completed work effort.

2.5 Integration and Communications

The SMV program of CCP has funded and managed ~30 projects over the last three years. These projects are grouped into four technology areas: Integrity, Optimization, Monitoring and Risk Assessment. Research results were submitted in the form of presentations, reports and software. The results of most of these studies so far has met expectations. There is a concern, however, that these research products might be filed away and thus not be made available to promote CO_2 storage technology. To publicize SMV efforts to a broad range of audiences, LBNL (Benson) was contracted to develop a plan for "Publication and Dissemination of Research Results" to be conducted in parallel with the larger CCP integration and communication effort. Five categories of publications are envisioned:

1) A large compilation of high quality, technical papers covering all areas of SMV research by a respected scientific society (e.g., AGU). The target audience includes technical specialists interested in geological sequestration of CO_2 and the IPCC.
2) A technical review article focusing on the principal technology areas of SMV (integrity, optimization, monitoring and risk assessment) (e.g., JPT, Oil & Gas Journal). The target audience includes scientists and engineers being introduced to CO_2 sequestration.
3) A technical review article similar to 2) but with more introductory treatment (e.g., Scientific American). The target audience includes NGOs. Regulators, government officials with an interest in science and technology.
4) A short, high impact "state-of-the-art" article (e.g., Science, Nature). The target audience includes government officials, scientific policymakers, NGOs and scientific press.
5) Brochure or pamphlet on geologic storage that highlights the accomplishments of the SMV (hard copy or web-based). The target audience includes general public, educators and regulators being introduced to the technology.

A book proposal for the large technical volume (1) has been submitted to the American Geophysical Union (AGU). Most of the Principal Investigators who were asked to submit a manuscript to this volume have responded in the positive. Should the volume be approved by AGU, submittal by March 30, 2004 and publication by fall 2004 is expected. This will allow enough time for the IPCC working group on CO_2 sequestration, meeting in December 2004, to incorporate needed documentation into their assessment. The remaining planned publications will present the story of CO_2 sequestration to scientists and engineers, government officials, regulators, NGOs and the general public.

The 2003 SMV Workshop will be held in Dublin, Ireland September 22-25. Most of the projects are expected to be complete or nearly so by that time. The workshop will offer an opportunity for TP PIs to vet their work among themselves and before the SMV team and external experts. This will allow modest adjustments to be made before project completion. The workshop will also offer the opportunity to encourage the participants to contribute to the publication efforts and to engage them on possible future CCP efforts.

2.5.1 Technical Report Integration Into Topical Reports

Task - 5.2 - Routine Project Reporting

Highlights

Contract has been executed and work is underway.

Summary

The purpose of this task is to develop a book (edited volume) and several overview articles based on results from the SMV team of the CO_2 Capture Project. We will develop a series of reports and publications that will be used to communicate the results of the SMV team's work to a variety of audiences that would benefit from this information. Target audiences include the staff of the member companies of the CCP JIP, technical specialists interested in geologic sequestration, NGO's, regulators, government officials, opinion makers, and the general public. The overview publications will be submitted between by November 30, 2003 with publication expected by mid-2004. The edited volume will be submitted by March 31, 200 and published before October 2004. This effort is being coordinated with the overall CCP integration and communications plan.

The CCP SMV team has contracted Lawrence Berkeley National Laboratory to implement a publication strategy that will disseminate the results of the ~30 SMV studies to diverse audiences ranging from technical specialists to the public. Table 7 matches the audience to the type of publication.

Table 7
Suggested products from the SMV Team for dissemination of results.

Audiences	Product	Description
• Technical staff from the member companies of the JIP • Technical specialists interested in geologic sequestration	Publication #1. Large compilation of technical papers (20-30 pages each) from all of the projects in the SMV; prefaced by an executive summary.	Peer reviewed, high quality technical document. Suitable for citation by the IPCC special study. Published as a book from a widely respected scientific society.
• Scientists and engineers being introduced to geologic sequestration, regulators	Publication #2. Technical review article, 20-30 pages long. Focused on major areas of the SMV, risk assessment, storage optimization, storage integrity and monitoring and verification.	Technical article to be published in widely distributed technical journal (e.g. JPT, Oil and Gas Journal).
• NGOs, regulators, government officials, public with an interest in science and technology, press	Publication #3. Technical review article, 20-30 pages long. Introduction to geologic storage followed by a description of the major areas of the SMV project, risk assessment, storage optimization, storage integrity and monitoring and verification	Article for a broad audience published in a widely read journal such as Scientific American or the equivalent.
• Government officials, scientific opinion makers, NGOs, scientific press	Publication #4. Short "State of the Technology Article" (3-5 pages) for highly influential scientific audience and government leaders.	Short article for high impact scientific journal (e.g. Science or Nature).
• General public, NGOs, press, educators, regulators being introduced to the technology	Publication #5. Brochure or pamphlet on geologic storage that highlights the contributions of the CCP JIP.	Hard copy & web-based description of geologic storage targeted to a non-tech audience. Emphasis on contributions of the CCP to geologic storage. Emphasize benefits of technology.

The following outlines the deliverables for the project:

1. Publication #1. Prepare an executive summary, introduction and conclusions that would introduce and summarize a compilation of all of the papers for each of the SMV projects. Organize and oversee a peer review for all of the final papers delivered to the SMV team.

2. Publication #2. In consultation with the SMV team, prepare a review article (approximately 30 pages) of the results from the SMV teams work. Submit to a widely available journal for technical specialists interested in geologic sequestration (e.g. JPT, Oil and Gas Journal, or others at the suggestion of the SMV team).

3. Publication #3. In consultation with the SMV team and the SMV team's communications consultant, prepare a review article (approximately 30 pages) of the results from the SMV teams work. Submit to a widely available journal for broad audience (e.g. Scientific American or others at the suggestion of the SMV team).

4. Publication #4. In consultation with the SMV team, prepare a short "State of the Technology" paper (approximately 3-5 pages) based on the results of the SMV teams work. Submit to a highly prestigious journal (e.g. Science or Nature).

5. Publication #5. Provide technical assistance to the SMV team's communications consultant to prepare a brochure or short pamphlet for the general public about Geologic Sequestration and the SMV team's projects.

Reports and Publications

None.

2.5.2 SMV 2003 Workshops – Future Project Venue

Highlights

Dublin, Ireland was selected for the 2003 SMV workshop to be held September 22-25. This choice was made to continue the alternation of venue between Europe and the US while staying within the allotted budget.

Summary

Past SMV workshops were held in Washington DC (2000), Potsdam (2001) and Santa Cruz (2002) to give technology providers an opportunity to present their progress and receive feedback from the SMV team and other participants. These meetings resulted in important re-scoping decisions that maintained the focus of research, identified gaps and allowed for needed budget adjustments. CDs with presentations were issued for each of the workshops. Presentations will be gathered prior to the meeting and issued on CDs at the meeting.

The 2003 SMV Workshop will be held in Dublin, Ireland, September 22-25. Invitations will be sent to PIs of all active projects that were in place in early 2003. Selective invitations will be made to PIs of selected past and newly contracted projects, to one or more NGCAS PIs. Selected individuals from the CCP Technical Advisory Board, government fenders (US DOE, EU, NorCap) and external experts (e.g., IEA, BGS) will also be invited. Most of the SMV team is expected to attend.

The intent of the workshop is to:

1) Review progress and make necessary adjustments in funding and deadlines,
2) Encourage PIs to arrive with draft manuscripts if possible,
3) Discuss plans for publishing and otherwise publicizing results (integration and communication), and
4) Discuss plans, if applicable for a new CCP project (or extension).

Reports and Publications

None.