Final Report
Strategic Center for Coal
Carbon Sequestration
FY 2010 Peer Review Meeting

Pittsburgh, Pennsylvania
March 15-19, 2010

U.S. DEPARTMENT OF ENERGY
OFFICE OF FOSSIL ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

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FINAL REPORT
STRATEGIC CENTER FOR COAL
CARBON SEQUESTRATION
FY 2010 PEER REVIEW MEETING

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MEETING SUMMARY AND RECOMMENDATIONS REPORT

NETL Project Manager and Peer Review Coordinator
José D. Figueroa
(412) 386-4966

Meeting Host Organization
Leonardo Technologies, Inc.
Massood Ramezan
(412) 386-6451

Review Panel
AMERICAN SOCIETY OF MECHANICAL ENGINEERS
Ian Duncan, Co-Chair, Peer Review Panel
Daniel J. Kubek, Co-Chair, Peer Review Panel
Richard Laudenat, Chair, Peer Review Executive Committee
Michael Tinkleman, Director, Research
ASME Center for Research and Technology Development
(202) 785-7394

Meeting Facilitator and Final Report
Ross Brindle, Energetics Incorporated
(410) 953-6239

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MEETING SUMMARY AND RECOMMENDATIONS REPORT

EXECUTIVE SUMMARY

The mission of the U.S. Department of Energy's (DOE) Office of Clean Coal (OCC) is to ensure the availability of ultra-clean, near-zero emission, abundant, and low-cost domestic energy from coal in order to fuel economic prosperity, strengthen energy security, and enhance environmental quality. The OCC is organized into nine technology programs. The OCC Carbon Sequestration technology program is administered by the DOE Office of Fossil Energy's National Energy Technology Laboratory (NETL). The Carbon Sequestration Program goal is the following:

> *By 2015, develop fossil fuel conversion systems that offer 90% CO_2 capture with 99% storage permanence at less than a 10% increase in the cost of electricity (COE) for Pre-Combustion Capture (IGCC) and less than 35% increase in COE for Post-Combustion Capture.*

In compliance with requirements from the Office of Management and Budget (OMB), DOE and NETL are fully committed to improving the quality of research projects in their programs. To aid this effort, DOE and NETL conducted a FY 2010 Carbon Sequestration Peer Review Meeting with independent technical experts to assess ongoing research projects and, where applicable, to make recommendations for individual project improvement.

In cooperation with Leonardo Technologies, Inc., the American Society of Mechanical Engineers (ASME) convened a panel of eight leading academic and industry experts on March 15–19, 2010 to conduct a five-day Peer Review of selected Carbon Sequestration Program research projects supported by NETL.

Overview of Office of Fossil Energy Carbon Sequestration Program Research Funding

The total funding of the16 projects reviewed, over the duration of the projects, is $67,572,758. Of this amount, $64,114,943 (95%) is funded by DOE, while the remaining $3,457,815 (5%) is funded by project partner cost sharing.

The 16 projects that were the subject of this Peer Review are summarized in Table ES-1 and in Section II of this report.

TABLE ES-1 CARBON SEQUESTRATION PROJECTS REVIEWED

Reference Number	Project No.	Title	Lead Organization	Principal Investigator	Total Funding[A]		Project Duration[A]	
					DOE	Cost Share	From	To
01	ORD-FY10.ESD.1610251.612	Pre-combustion Solvents, Membranes, and Sorbents - Synthesis, Characterization, and Lab-Scale Performance Testing	NETL–ORD	David Luebke	$709,200	$0	10/01/2009	09/30/2010
02	FWP-FE-10-002	High Temperature Polymer-Based Membrane Systems for Pre-Combustion Carbon Dioxide Capture	Los Alamos National Laboratory	Kathryn A. Berchtold	$600,000	$0	10/01/2009	01/31/2011
03	ORD-GEC.1610251.600.B	Geologic Sequestration - Wellbore/Seal Integrity Project	National Energy Technology Laboratory	Brian Strazisar	$1,045,000	$0	10/01/2009	09/30/2010
04	FWP-45502/FWP-58159	Sequestration of CO_2 in Basalt Formations	Pacific Northwest National Laboratory	B. Peter McGrail	$1,855,000	$0	10/01/2002	09/30/2010
05	FWP-FE-10-001 Task 3	Systems Modeling & Science for Geologic CO_2 Sequestration	Los Alamos National Laboratory	Rajesh Pawar	$1,000,000	$0	10/01/2009	09/30/2012
06	FWP-ESD09-056 Task 5	Regional Modeling of Large-Scale Hydrologic Impact of CO_2 Storage	Lawrence Berkeley National Laboratory	Jens Birkholzer	$2,059,000	$0	10/01/2006	09/30/2012
07	FWP-ESD09-056 Task 2	GEO-SEQ	Lawrence Berkeley National Laboratory	Barry Freifeld	$11,050,000	$0	05/01/2000	09/30/2012
08	DE-NT0006642	Shallow Carbon Sequestration Demonstration Pilot	City Utilities of Springfield, MO	Gary J. Pendergrass	$2,362,349	$590,587	10/01/2008	12/31/2010
09	FWP-FEW-0174 Task 3	Injection & Reservoir Hazard Management: Fault Geomechanics and Integrated CO_2 Leakage Simulation Applied to Geologic Storage	Lawrence Livermore National Laboratory	Walt McNab	$1,500,000	$1,500,000	06/01/2008	09/30/2010
10	FWP-FEW-0174 Task 2	Fresh Water Generation from Saline Formation-Pressured Carbon Storage	Lawrence Livermore National Laboratory	Roger Aines	$1,100,000	$0	06/01/2008	02/01/2011
11	DE-NT0004730	Carbon Sequestration Monitoring Activities	University of Wyoming	Carol D. Frost	$2,381,254	$823,302	09/01/2008	08/31/2010
12	DE-FC26-04NT42262	Basic Science of Retention Issues, Risk Assessment & Measurement, Monitoring, & Verification for Geologic CO_2 Sequestration (ZERT)	Montana State University	Lee H. Spangler	$24,061,140	$468,962	10/01/2004	09/30/2010
13	FWP-AACH-139	New Approach for Long-term Monitoring of Leaks from Geologic Sequestration	Brookhaven National Laboratory	Lucian Wielopolski	$1,050,000	$0	10/01/2007	09/30/2010
14	ORD-GEC.1610251.600.A	National Risk Assessment Program (NRAP)	National Energy Technology Laboratory	Grant Bromhal	$3,750,000	$0	07/01/2009	06/30/2010
15	OSAP-CO2-EOR LCA	Assessing Net Storage Potential of CO_2-Flood Enhanced Oil Recovery: A Life Cycle Analysis Perspective	National Energy Technology Laboratory	Robert Dilmore	$75,000	$0	01/02/2009	03/30/2010
16	OSAP-41817.401.01.01	Assessment of Power Plants that Meet Proposed Greenhouse Gas Emission Performance Standards	National Energy Technology Laboratory	Eric Grol	$112,000	$0	10/26/2007	11/14/2009
				TOTALS	$64,114,993	$3,457,815		

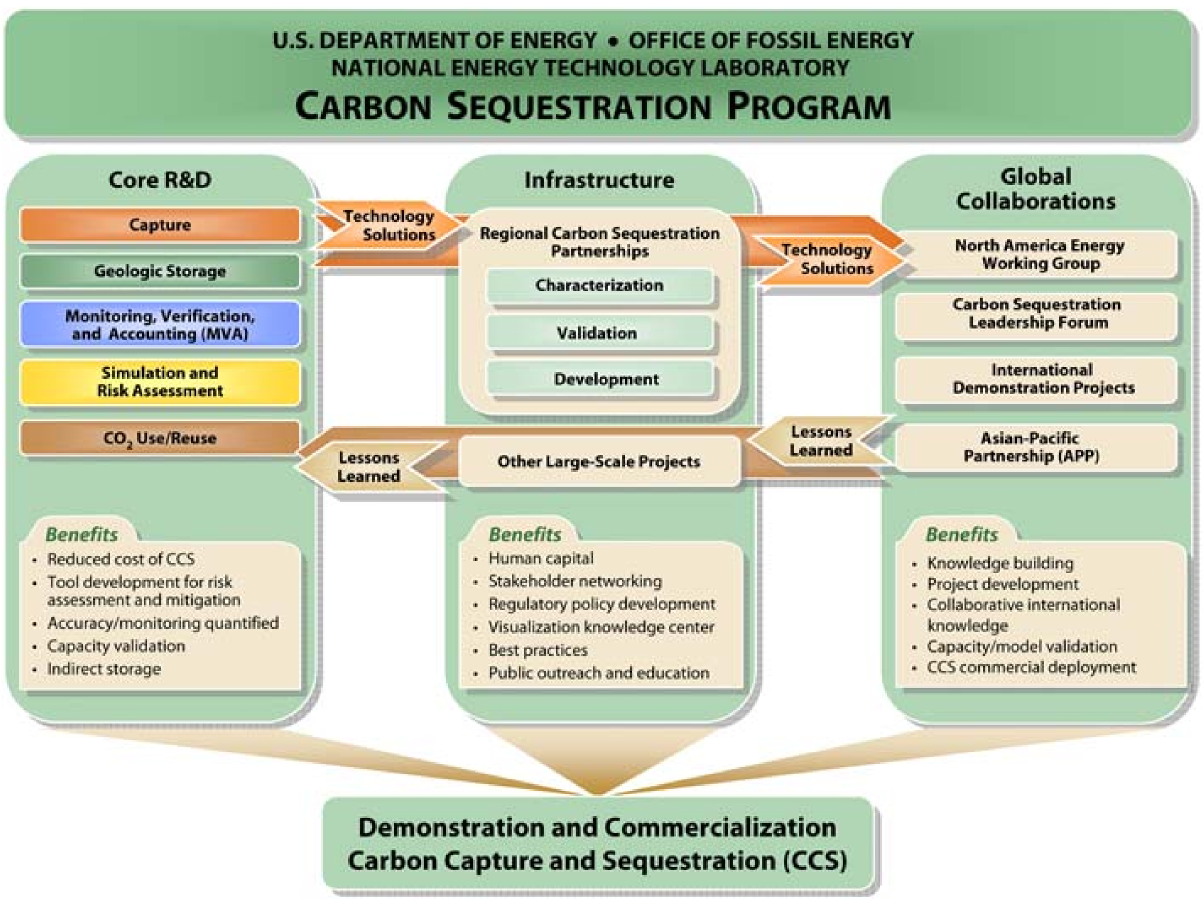
Note: A: Funding amounts and project durations have been obtained from project summaries submitted by the principal investigator.

NETL CARBON SEQUESTRATION PROGRAM OVERVIEW

The Carbon Sequestration Program significantly contributes to the President's goal of developing technologies that substantially reduce greenhouse gas emissions. NETL envisions a technology portfolio of safe, cost-effective, commercial-scale greenhouse gas capture, storage, and mitigation technologies that will be available for commercial deployment beginning in 2020.

Program Areas:

The Carbon Sequestration Program involves three key elements for technology development: Core Research and Development (R&D), Infrastructure, and Global Collaborations. Core R&D, driven by industry technology needs, segregates those needs into focus areas to more efficiently obtain solutions that can be tested and deployed in the field. The Infrastructure element includes the Regional Carbon Sequestration Partnerships (RCSPs) and other large-volume field tests in which various CCS technology options are validated and their efficacy is confirmed. Lessons learned from the Infrastructure element are fed back to Core R&D to guide future technology research and development. Global Collaborations benefit from technology solutions developed in the Core R&D and Infrastructure elements; in turn, these collaborations feed back lessons learned to Infrastructure and Core R&D from the international demonstration projects and partnerships



Source: National Energy Technology Laboratory.

Overview of the Peer Review Process

NETL requested that ASME assemble a Carbon Sequestration Peer Review Panel (hereinafter referred to as the Panel) of recognized technical experts to provide recommendations on how to improve the management, performance, and overall results of each individual research project. Each project team prepared a detailed project information form containing an overview of the project's purpose, objectives, and achievements, and a presentation to be given at the Peer Review Meeting. The Panel received the project information forms and presentations prior to the Peer Review Meeting.

At the meeting, each research team made an uninterrupted 45- to 60-minute PowerPoint presentation that was followed by a 30- to 40-minute question-and-answer (Q&A) session with the Panel. After the principal investigator (PI) and project team left the room, the Panel had a 30- to 40-minute discussion about the strengths, weaknesses, recommendations, and action items for each project. To facilitate a more open and free discourse of project-related material between the project team and the Panel, all sessions were limited to the Panel, ASME, project team members, and DOE/NETL personnel.

After the group discussions, each Panel member individually evaluated the 16 projects, providing written comments based on a predetermined set of review criteria. For each of the nine review criteria, the individual reviewer was asked to score the project as one of the following:

Effective (5)

Moderately Effective (4)

Adequate (3)

Ineffective (2)

Results Not Demonstrated (1)

The Panel occasionally had divergent views of a project. In the extreme case, this divergence is reflected in projects receiving both 1 and 5 ratings in a particular criterion. This result should not be taken as an indication that the Panel was indecisive; rather, this reflects the varied backgrounds and differing perspectives of a diverse Panel. Such diversity is a strength allowing the Panel, as a whole, to review a wide range of projects on varied topics with a comparable overall level of expertise.

Figure ES-2 shows the overall average score, combining all nine review criteria, for the 16 projects.

FIGURE ES-2 AVERAGE SCORING, BY PROJECT

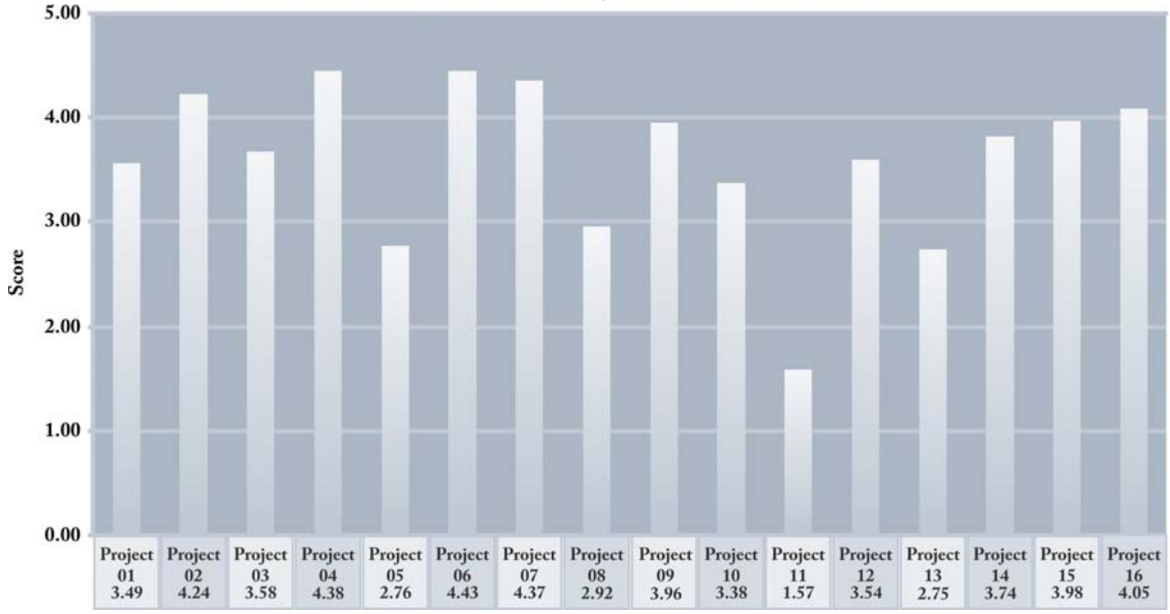


Table ES-3 shows the overall average across all 16 projects reviewed, as well as the highest and lowest averages for an individual project for each of the nine review criterion.

TABLE ES-3 AVERAGE SCORING, BY REVIEW CRITERION

Criterion	Project Average	Highest Project Average	Lowest Project Average*
1. Scientific and Technical Merit	3.7	4.9	2.5/1.3
2. Existence of Clear, Measurable Milestones	3.6	4.3	3.1/2.3
3. Utilization of Government Resources	3.7	4.8	2.8/1.6
4. Technical Approach	3.6	4.9	2.5/1.4
5. Rate of Progress	3.6	4.5	2.4/1.3
6. Potential Technology Risks Considered	3.3	4.3	2.4/1.5
7. Performance and Economic Factors	3.1	4.4	2.0/1.5
8. Anticipated Benefits, if Successful	4.0	4.9	2.3/2.0
9. Technology Development Pathways	3.4	4.8	2.5/1.4

* To present a more accurate view of the lowest scores, two values have been given. The first value is the lowest average score of all projects except project 11: DE-NT0004730, Carbon Sequestration Monitoring Activities. The second value is the lowest average score of all projects. This distinction is made because project 11 received significantly lower scores than the other projects reviewed.

For more on the overall evaluation process and the nine review criteria, see Section III.

Each project was categorized based on its stage of development, which ranged from fundamental research to proof-of-concept, as described in Table ES-4. This categorization enabled the Panel to appropriately score the Performance and

Economic Factors and Technology Development Path criteria by providing context for the anticipated level of economic and developmental data for each project.

TABLE ES-4 DESCRIPTION OF DEVELOPMENT STAGES

Stage of Research	Description
Fundamental Research	The project explores and defines technical concepts or fundamental scientific knowledge. Projects are laboratory-scale and, traditionally but not exclusively, are the province of academia.
Applied Research	The project presents a laboratory- or bench-scale proof of the feasibility of potential applications of a fundamental scientific discovery.
Prototype Testing	The project develops and tests a prototype technology or process in the laboratory or field, maintaining predictive modeling or simulation of performance and evaluating scalability.
Proof-of-Concept	The project develops and tests a pilot-scale technology or process for field testing and validation at full scale, but is not indicative of a long-term commercial installation.
Major Demonstration *Not applicable in this peer review.*	The project develops a commercial-scale demonstration of energy and energy-related environmental technologies, generally with the intent of becoming the initial representation of a long-term commercial installation.

A summary of key project findings as they relate to individual projects can be found in Section IV of this report. Process considerations and recommendations for future project reviews are found in Section V.

For More Information

For more information concerning the contents of this report, contact the NETL Peer Review Coordinator, José D. Figueroa, at (412) 386-4966 or Jose.Figueroa@netl.doe.gov.

I. INTRODUCTION

In 2010, the American Society of Mechanical Engineers (ASME) was invited to provide an independent, unbiased, and timely peer review of selected projects within the U.S. Department of Energy (DOE) Office of Fossil Energy Carbon Sequestration Program (administered by the Office of Fossil Energy's National Energy Technology Laboratory [NETL]). On March 15–19, 2010, ASME convened a panel of eight leading academic and industry experts to conduct a five-day peer review of selected Carbon Sequestration research projects supported by NETL. This report contains a summary of the findings from that review.

Compliance with Office of Management and Budget Requirements

DOE, the Office of Fossil Energy, and NETL are fully committed to improving the quality and results of their projects. The peer review of selected projects within the Carbon Sequestration Program was designed to comply with requirements from the Office of Management and Budget.

ASME Center for Research and Technology Development (CRTD)

All requests for peer reviews are organized under ASME's Center for Research and Technology Development (CRTD). CRTD's Director of Research, Dr. Michael Tinkleman, with advice from the chair of the ASME Board on Research and Technology Development, selects an executive committee of senior ASME members that is responsible for reviewing and approving all Panel members and ensuring that there are no conflicts of interest within the Panel or the review process. In consultation with NETL, ASME formulates the review meeting agenda, provides information advising the principal investigators (PIs) and their colleagues on how to prepare for the review, facilitates the review session, and prepares a summary of the results. A more extensive discussion of the ASME peer review methodology used for the Carbon Sequestration Peer Review Meeting is provided in Appendix A. A copy of the meeting agenda is provided in Appendix B, and profiles of the Panel members are provided in Appendix C.

Overview of the Peer Review Process

ASME was selected as the independent organization to conduct a five-day peer review of 16 Carbon Sequestration Program projects. ASME performed this project review work as a subcontractor to Leonardo Technologies, Inc., a NETL prime contractor. NETL selected the 16 projects, while ASME organized an independent review panel of eight leading academic and industry power plant technology experts. Prior to the meeting, project PIs submitted an 11-page written summary (Project Information Form) of their project's purpose, objectives, and progress. The PI's also submitted their PowerPoint presentations to the Panel prior to the meeting. This project information, available prior to the meeting, allows the Panel to come to the meeting fully prepared with the necessary project background information.

At the meeting, each research team made a 45- to 60-minute oral presentation, followed by a 30- or 40-minute question-and-answer (Q&A) session with the Panel and a 30- to 40-minute Panel discussion of each project. The length of the presentation and Q&A session depended primarily on the perceived time requirement for the PI to go through the presentation material due to a number of factors, such as the project's complexity, duration, and breadth of scope. Based on lessons learned from prior peer reviews and the special circumstances associated with the Carbon Sequestration Program's research, ASME decided that both the PI presentations and Q&A sessions with the Panel for the Carbon Sequestration Peer Review were to be held as closed sessions, limited to the Panel, ASME project team members, and DOE/NETL personnel. The closed sessions ensured open discussions between the PIs and the Panel. Panel members were also instructed to hold the discussions that took place during the Q&A session as confidential.

Each member of the Panel individually evaluated the project presented and provided written comments based on a predetermined set of review criteria. This publically available document, prepared by ASME, provides a general overview of the Carbon Sequestration Peer Review and the projects reviewed therein.

Peer Review Criteria and Peer Review Criteria Forms

ASME developed a set of agreed-upon review criteria to be applied to the projects reviewed at this meeting. ASME provided the Panel and PIs with these review criteria in advance of the Peer Review Meeting; and assessment sheets with the review criteria were pre-loaded (one for each project) onto laptop computers for each Panel member. During the meeting, the Panel members assessed the strengths and weaknesses of each project before providing both recommendations and action items. A more detailed explanation of this process and a sample Peer Review Criteria Form are provided in Appendix D.

The following sections of this report summarize findings from the Carbon Sequestration Program Peer Review Meeting, organized as follows:

II. *Summary of Projects Reviewed in the FY 2010 Carbon Sequestration Peer Review*:

    A list of the 16 projects reviewed and the selection criteria

III. *An Overview of the Evaluation Scores in FY 2010*:

    Average scores and a summary of evaluations, including analysis and recommendations

IV. *Summary of Key Project Findings*:

    An overview of key findings from project evaluations

V. *Process Considerations for Future Peer Reviews*:

    Lessons learned in this review that may be applied to future reviews

II. SUMMARY OF PROJECTS REVIEWED IN FY 2010 CARBON SEQUESTRATION PEER REVIEW

NETL selected key projects within the Carbon Sequestration Program, including projects being conducted in NETL's Office of Research and Development (ORD), Office of Systems Analysis and Planning (OSAP), and the Advanced Research Program, to be reviewed by the independent Panel. Selected projects are listed below alongside the name of the organization leading the research. A short summary of each of the above projects is presented in Appendix E.

PROJECTS REVIEWED

01: ORD-FY10.ESD.1610251.612
Pre-combustion Solvents, Membranes, and Sorbents - Synthesis, Characterization, and Lab-Scale Performance Testing—*National Energy Technology Laboratory, Office of Research and Development*

02: FWP-FE-10-002
High Temperature Polymer-Based Membrane Systems for Pre-Combustion Carbon Dioxide Capture—*Los Alamos National Laboratory*

03: ORD-GEC.1610251.600.B
Geologic Sequestration - Wellbore/Seal Integrity Project—*National Energy Technology Laboratory, Office of Research and Development*

04: FWP-45502/FWP-58159
Sequestration of CO_2 in Basalt Formations—*Pacific Northwest National Laboratory*

05: FWP-FE-10-001 TASK 3
Systems Modeling & Science for Geologic CO_2 Sequestration—*Los Alamos National Laboratory*

06: FWP-ESD09-056 TASK 5
Regional Modeling of Large-Scale Hydrologic Impact of CO_2 Storage—*Lawrence Berkeley National Laboratory*

07: FWP-ESD09-056 TASK 2
GEO-SEQ—*Lawrence Berkeley National Laboratory*

08: DE-NT0006642
Shallow Carbon Sequestration Demonstration Pilot—*City Utilities of Springfield, MO*

09: FWP-FEW-0174 TASK 3
Injection & Reservoir Hazard Management: Fault Geomechanics and Integrated CO_2 Leakage Simulation Applied to Geologic Storage—*Lawrence Livermore National Laboratory*

10: FWP-FEW-0174 TASK 2
Fresh Water Generation from Saline Formation-Pressured Carbon Storage—*Lawrence Livermore National Laboratory*

11: DE-NT0004730
Carbon Sequestration Monitoring Activities—*University of Wyoming*

12: DE-FC26-04NT42262
Basic Science of Retention Issues, Risk Assessment & Measurement, Monitoring, & Verification for Geologic CO_2 Sequestration (ZERT)—*Montana State University*

13: FWP-AACH-139
New Approach for Long-term Monitoring of Leaks from Geologic Sequestration—*Brookhaven National Laboratory*

14: ORD-GEC.1610251.600.A
National Risk Assessment Program (NRAP)—*National Energy Technology Laboratory, Office of Research and Development*

15: OSAP-CO2-EOR LCA
Assessing Net Storage Potential of CO_2-Flood Enhanced Oil Recovery: A Life Cycle Analysis Perspective—*National Energy Technology Laboratory*

16: OSAP-41817.401.01.01
Assessment of Power Plants that Meet Proposed Greenhouse Gas Emission Performance Standards—*National Energy Technology Laboratory, Office of Systems, Analysis and Planning*

III. AN OVERVIEW OF THE EVALUATION SCORES FOR THE CARBON SEQUESTRATION PROGRAM

For each of the nine review criteria, individual reviewers were asked to score the project as one of the following:

Effective (5)

Moderately Effective (4)

Adequate (3)

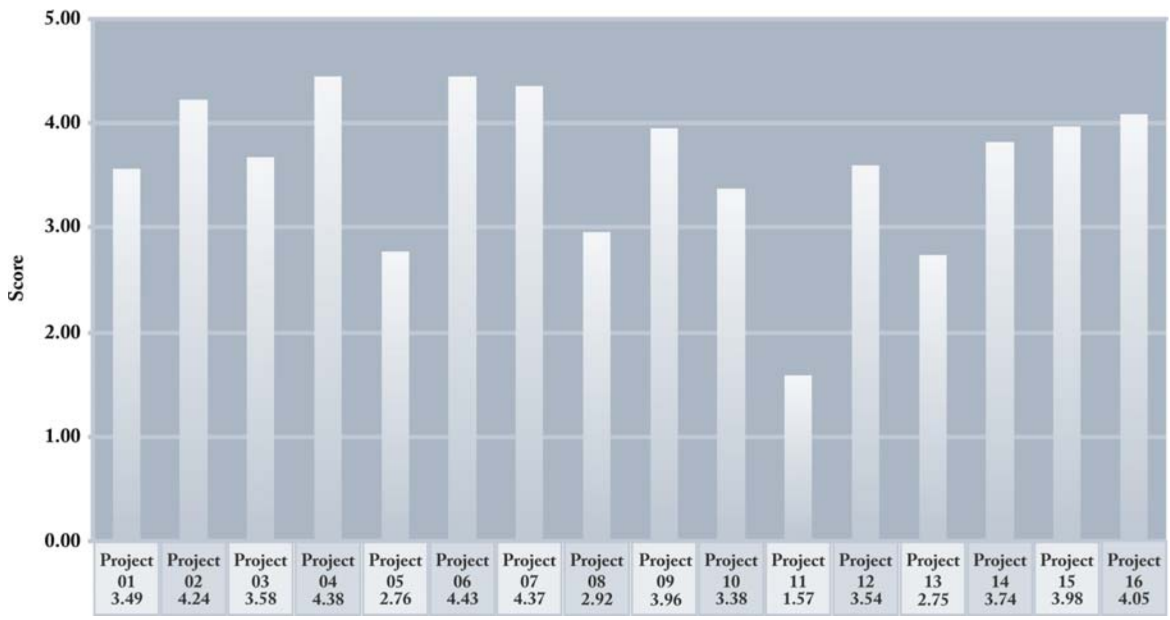
Ineffective (2)

Results Not Demonstrated (1)

The average scores for all the projects and across each rating criterion indicate that, overall, the Carbon Sequestration Program is strong, with opportunities for improvement. The program consists primarily of well-managed and well-staffed projects aimed at developing innovative and marketable technologies that have considerable potential to provide valuable benefits to the electric power industry.

Figure 1 shows the average project scores, combining the average of the nine review criteria, for each of the 16 projects reviewed. The Panel viewed most projects favorably: five of the projects received an average project score at or above 4.0; six of the projects were scored between 3.0 and 4.0 (with two of those projects nearly attaining scores of 4.0); three projects between 2.0 and 3.0 (all of which rated above 2.7); and one project with an average score below 2.0. The project with the lowest average score earned a 1.6, while the project with the highest average score earned a 4.4. The average of the 16 project scores was 3.6. These results indicate that the Panel, on average, deemed the projects more than adequate.

FIGURE 1 AVERAGE SCORING, BY PROJECT



General conclusions about the Carbon Sequestration Program can also be drawn by looking at the average scores for each of the nine review criteria, which are shown in Table 1. Nearly all of the criteria received average scores of 3.6 or higher, reflecting that NETL and DOE are more than adequately leveraging government resources by funding mostly well-managed projects that are developing innovative, economical, and scientifically rigorous technologies. The data also show that most projects have great potential to benefit the carbon capture and sequestration (CCS) field. However, the project teams, on average, could have been more effective at conducting preliminary economic and risk analyses and at closely considering the commercial applications of the technologies. While the Panel understood that these are challenging objectives for Applied Research Projects in CCS, this is a DOE/NETL Review Criteria and the Projects are obligated to address these issues as best as they can.

TABLE 1 AVERAGE SCORING, BY REVIEW CRITERION

Criterion	Project Average	Highest Project Average	Lowest Project Average*
1. Scientific and Technical Merit	3.7	4.9	2.5/1.3
2. Existence of Clear, Measurable Milestones	3.6	4.3	3.1/2.3
3. Utilization of Government Resources	3.7	4.8	2.8/1.6
4. Technical Approach	3.6	4.9	2.5/1.4
5. Rate of Progress	3.6	4.5	2.4/1.3
6. Potential Technology Risks Considered	3.3	4.3	2.4/1.5
7. Performance and Economic Factors	3.1	4.4	2.0/1.5
8. Anticipated Benefits, if Successful	4.0	4.9	2.3/2.0
9. Technology Development Pathways	3.4	4.8	2.5/1.4

* To present a more accurate view of the lowest scores, two values have been given. The first value is the lowest average score of all projects except project 11: DE-NT0004730, Carbon Sequestration Monitoring Activities. The second value is the lowest average score of all projects. This distinction is made because project 11 received significantly lower scores than the other projects reviewed.

A copy of the Peer Review Criteria Form and a detailed explanation of the review process are provided in Appendix D.

IV. SUMMARY OF KEY FINDINGS

This section summarizes key findings from across the group of the 16 projects that were evaluated.

General Project Strengths

The Panel found the majority of projects to be sound, commending DOE for presenting a high-quality, diverse portfolio of projects with ambitious goals and significant potential to contribute to carbon sequestration efforts. As reflected in Table I, the strongest-rated area across the projects was anticipated benefits, indicating the Panel's perception that, overall, NETL's Carbon Sequestration Program is addressing the key research areas and technology challenges in the carbon capture and sequestration (CCS) field.

In general, the Panel deemed project management and leadership of the projects impressive. They indicated that most of the project teams are experienced in and passionate about their areas of research. The Panel considered most projects cost effective, achieving promising results and producing valuable tools at relatively low expense.

The majority of projects were conducted by national laboratories, and the Panel applauded both the impressive fundamental science being conducted and the ability of the laboratories to collaborate and, in some cases, integrate their efforts. In particular, the Panel was complimentary of those projects which sought to continue benchmarking work and fill knowledge gaps, providing widely-accessed reports for existing and new technology implementation.

The Panel was pleased by the modeling efforts undertaken by many of the teams because they reflect a responsible, balanced use of funding to expand the range of application of experimental studies. Specifically, the Panel specified that modeling efforts early in a project are an extremely efficient and beneficial means of narrowing project focus.

The highest-rated projects were Project 04, "Capture and Sequestration Systems Support: Basalt Formation Geologic Sequestration," conducted by Pacific Northwest National Laboratory; Project 06, "Regional Modeling of Large-Scale Hydrologic Impact of CO_2 Storage," conducted by Lawrence Berkeley National Laboratory; and Project 07, "GEO-SEQ," conducted by Lawrence Livermore National Laboratory. These projects received an average rating (across all nine criteria) of approximately 4.4 out of 5.0. Project 02, "High Temperature Polymer-Based Membrane Systems for Pre-Combustion Carbon Dioxide Capture," conducted by Los Alamos National Laboratory and Project 16, "Assessment of Power Plants That Meet Proposed Greenhouse Gas Emission Performance Standards" also received average scores above 4.0. All five of these projects were lauded by the Panel for achieving significant results due to project managers and teams that not only practiced sound science and had strong technical approaches, but also worked to maintain the applicability of the research effort to industry needs and program goals.

General Project Weaknesses

The Performance and Economic Factors and Potential Technology Risks Considered criteria had the lowest average scores (3.1 and 3.3, respectively).

According to the rating definitions, these scores indicate, on average, that the program is Adequate in these areas. However, just as several projects performed well under these criteria, these low average scores also indicate that particular projects underperformed relative to the standards identified by the evaluation criterion for their development stages as noted on page viii Table ES-4. Specifically, the Panel found that several project teams did not identify and consider the commercial economic viability and risks (both market and technical) of their technology in a meaningful way. Although the Panel recognizes that CO_2 storage projects are primarily concerned with demonstrating 99 percent storage permanence, with economic considerations being of secondary importance, the cost-effectiveness of storage options is still an essential consideration in the commercial viability of CCS and was rated accordingly by the Panel.

The Panel recognized that several projects did not fully align their research with industry needs. These projects did not adequately consider end-use technology applications and/or were poorly aligned with the overarching objective of the NETL Carbon Sequestration Program. The Panel surmised that this may be partly due to a lack of collaboration with, and guidance from, outside stakeholders in the research. These projects also tended to be the same ones that scored low in the economic and risk criteria. This is likely because industry interactions tend to direct teams towards more practical economic considerations and help to minimize market risk by increasing the likelihood that real-world conditions are considered during the technology's testing and development. The Panel specifically pointed out, however, that while some projects lacked alignment with the needs of industry, NETL itself has a long history of collaborating with industry and developing partnerships.

Lastly, while some projects performed well in the Existence of Clear, Measurable Milestones criterion, the Panel noted that many milestones, even in projects that performed very high in the other criteria, were simply descriptions of particular tasks (i.e., “Perform the experiment”), rather than measurable technical and economic performance metrics (i.e., “Achieve a specific result”).The Panel noted that such milestones enabled projects to prematurely advance to larger scales than advisable in light of actual performance. This issue both reflected and contributed to the failure of some projects to consider the full economic and technical implications of the chosen research approach.

Issues for Future Consideration

While many of the recommendations provided by the Panel were technical in nature and specific to the particular project’s technology, several overarching issues emerged. The first was with regard to milestones: in general, project milestones reflected output metrics such as the completion of a task, rather than an outcome. For example compare “software test completed” to “software test revealed simulation accuracy of better than 99%.” Output metrics are also far less useful when trying to move a technology toward commercialization. The Panel recommends that project milestones be reviewed and, as appropriate, be restated so as to reflect outcomes. Creating measurable milestones with regard to technical and economic factors will help projects stay on track toward project and program goals, and may also contribute to projects performing better in the Performance and Economic Factors, Potential Technology Risks Considered, and Technology Development Pathways criteria.

The Panel also cautioned against hyperbole and a lack of attention to word choice (e.g., “catastrophic”), noting that several projects were not precise in their descriptions of the various factors related to carbon sequestration; consequently, these comments could be taken out of context and/or misused. The Panel suggests that all project teams be conscious of the potential for misunderstanding publicly available comments.

The Panel emphasized the importance of communication through public outreach and education and collaboration with industry. The Panel recommends that all project teams engage potential stakeholders and verify their results with the external carbon sequestration community, particularly through industry and regional partnerships, when disseminating information. This additional direction could help to keep the project aligned with industry needs and related CCS research initiatives, and can help ensure the coherence of all information presented to the public.

Communication was noted as particularly important for modeling projects because of the wide array of models and codes in use and under development. To avoid duplication of work, researchers must stay informed of other modeling efforts and must understand how their project fits into the larger modeling picture and contributes to innovative developments in the CCS industry. Additionally, the Panel indicated that a suite of models from the oil and gas industry could offer important information, even if many of them are not entirely applicable to CCS.

The Panel also noted the need for additional focus on risk management and analysis as theme that arose in the portfolio of CCS projects reviewed. The Panel suggested that an integrated risk management approach to the program’s project portfolio would be beneficial because of the importance of public acceptance and confidence in CCS. One way to integrate this approach would be to combine risk management with the Monitoring Validation and Assessment area of the CCS Program. When publically discussing risk, the presentation of information should be carefully considered to prevent misunderstandings.

V. PROCESS CONSIDERATIONS FOR FUTURE PEER REVIEWS

The Panel and DOE/NETL managers involved in the Peer Review offered positive feedback on the review process and constructive comments for improving future peer reviews. These comments were provided at the conclusion of the Peer Review Meeting. The following is a brief summary of ideas recommended for consideration when planning future peer review sessions.

General Process Comments

All involved unanimously agreed that the current peer review process requires little or no modification to remain effective. There was high praise both for the facilitation of the meeting and the superb work of the support staff. Panel members found the computerized score tabulation method effective and beneficial because it permitted quick display of a project's preliminary average score and allowed the Panel to record strengths, weaknesses, recommendations, and action items for individual projects in a timely manner. The Panel members greatly appreciated and found adequate the time they were given prior to the Peer Review Meeting to read through the project information documents, and noted the efficiency of the SharePoint site from which they could download all of the project documents.

The Panel found that nearly all projects were presented well, with the exception of one project, which was presented by a contracts manager who was not a technically-versed project team member. The Panel acknowledged that the presence of other project partners enhanced the ability of the project team to respond to questions; the Panel recommends that the presence of other project partners at the review be encouraged for all projects, particularly those projects where the principal investigator (PI) may not be able to fully answer technical questions. The Panel was also pleased with the presenters' openness to recommendations, noting that they answered questions honestly without being defensive. It was also helpful to have the PI wait outside the meeting room during the Panel's internal discussions because occasionally it was necessary for the Panel to call the PI back to help clarify a particular point.

Meeting Agenda

The Panel indicated that the meeting agenda was well structured and provided adequate time for presentations, questioning, and subsequent Panel discussion without making the Panel feel rushed or overburdened. In general, the Panel was pleased with the time given to each aspect of the peer review process and noted that allotting additional time for the presentation and question and answer session for the more complex projects was an improvement over prior peer reviews.

The diverse areas of Panel members' expertise offered other members needed insight on various topics during discussion, providing more accurate and comprehensive ratings and comments.

Presentations

The Panel found that project presentations and the review process were enhanced by the DOE presentation template and DOE's efforts to familiarize the PIs with the presentation process. The Panel urged DOE to continue to emphasize the importance of the template in future reviews.

The Panel indicated that in some presentations there was an overabundance of administrative information which detracted from time spent discussing material that was more germane to the review. Project management information in excess of core requirements should be made available as background information and be excluded from the actual presentation. The Panel also recommended that the number of presentation slides be limited to 50 slides and that discussions of prior phase work should be limited unless they are critical to understand the current phase under review.

Evaluations

While the Panel noted that their introduction to the review process was quick and effective, there was some ambiguity on the context through which the Panel should evaluate certain criteria. The Panel had several lengthy discussions throughout the peer review process in an attempt to gain consensus on criteria interpretation, making several observations and recommendations for future peer reviews.

Several discussions ensued around the Existence of Clear Measurable Milestones criterion, focusing mainly on whether the reviewers should judge a project on the actual existence, clarity, and achievement of milestones or on the meaningfulness of the milestones for tracking project progress and results. DOE clarified that the rating criteria definitions are intended to guide the Panel, but that each Panel member should draw upon his own experience to determine the value of a project with respect to each criterion. In response, the Panel recommended that more time be spent on this topic during the initial orientation to the peer review process.

The Panel came to consensus on several other issues related to rating criteria definitions. First, the Panel agreed that the criterion Anticipated Benefits, If Successful should be based on a project's expected benefits associated with the current project scope, not on its expected value if all recommendations and action items are implemented. Second, the Panel clarified that projects should be rated under the various criteria (e.g., Utilization of Government Resources) according to each project's applicability and benefit to the overall Carbon Sequestration Program, not to the ancillary benefits the project may provide. The Panel recommends that the facilitator should make both of these distinctions explicit at the onset of the peer review process.

There were several instances in which the Panel felt it could not evaluate a project under a particular criterion and discussed the possibility of adding a Not Applicable (N/A) option to the project rating scale. The Panel explored both the benefits and disadvantages to such an addition, noting that while an N/A option seemed to be the only intuitive rating for certain projects (particularly for the Performance and Economic Factors criterion), the absence of an N/A rating forced the Panel to carefully discuss the project as related to the criterion.

On a few occasions, the Panel recognized that input from the NETL Program Manager during the discussion was necessary to clarify a broader programmatic issue related to the project being evaluated. The Panel appreciated the Program Manager's assistance in these cases because his input provided important context that helped the Panel better understand the project being reviewed.

Review Panel

The Panel thanked DOE for the opportunity to participate in this Peer Review, citing it as an enjoyable and educational experience.

APPENDICES

APPENDIX A: ASME PEER REVIEW METHODOLOGY

The American Society of Mechanical Engineers (ASME) has been involved in conducting research since 1909 when it started work on steam boiler safety valves. Since then, the Society has expanded its research activities to a broad range of topics of interest to mechanical engineers. ASME draws on the impressive breadth and depth of technical knowledge among its members and, when necessary, experts from other disciplines for participation in ASME-related research programs. In 1985, ASME created the Center for Research and Technology Development (CRTD) to coordinate ASME's research programs.

As a result of the technical expertise of ASME's membership and its long commitment to supporting research programs, the Society has often been asked to provide independent, unbiased, and timely reviews of technical research by other organizations, including the federal government. After several years of experience in this area, the Society developed a standardized approach to reviewing research projects. This section provides a brief overview of the review procedure established for the U.S. Department of Energy (DOE)/National Energy Technology Laboratory (NETL) FY 2010 Carbon Sequestration Peer Review.

ASME Knowledge and Community Sector

One of the five sectors responsible for the activities of ASME's 127,000 members worldwide—the Knowledge and Community Sector—is charged with disseminating technical information, providing forums for discussions to advance the mechanical engineering profession, and managing the Society's research activities.

Board on Research and Technology Development

ASME members with suitable industrial, academic, or governmental experience in the assessment of priorities for research and development, as well as in the identification of new or unfulfilled needs, are invited to serve on the Board on Research and Technology Development (BRTD) and to function as liaisons between BRTD and the appropriate ASME sectors, boards, and divisions. The BRTD has organized more than a dozen research committees in specific technical areas.

Center for Research and Technology Development

The Center for Research and Technology Development (CRTD), created in 1985, has undertaken the mission to effectively plan and manage ASME's collaborative research activities to meet the needs of the mechanical engineering profession, as defined by the ASME members. The CRTD is governed by the BRTD, and day-to-day operations of the CRTD are handled by the director of research and his staff. The director of research serves as staff to the Peer Review Executive Committee, handles all logistical support for the Panel, provides facilitation of the actual review meeting, and prepares all summary documentation.

Carbon Sequestration Peer Review Executive Committee

For each set of projects reviewed, the BRTD convenes a Peer Review Executive Committee to oversee the review process. The Executive Committee is responsible for guaranteeing that all ASME rules and procedures are followed, reviewing and approving the qualifications of those asked to sit on the Panel, ensuring that there are no conflicts of interest in the review process, and reviewing all documentation coming out of the project review. There must be at least two members of the Peer Review Executive Committee, all of whom must have experience relevant to the program being reviewed. Members of the FY 2010 Carbon Sequestration Peer Review Executive Committee were as follows:

Richard T. Laudenat, Chair. Mr. Laudenat is the senior vice president of the ASME Knowledge and Communities Sector. He was previously a vice president of the ASME Energy Conversion Group and was a member of the ASME Energy Committee.

Allen Robinson, Ph.D. Dr. Robinson is Associate Professor of Mechanical Engineering at Carnegie Mellon University. He brings to the Executive Committee his special focus on combustion-generated air pollution, biomass combustion, and heat and mass transfer in porous media.

Carbon Sequestration Peer Review Panel

The Carbon Sequestration Peer Review Executive Committee accepted résumés for proposed Carbon Sequestration Peer Review Panel members from CRTD and from the DOE/NETL program staff. From these sources, the ASME Peer Review Executive Committee selected an eight-member review panel and agreed that they had the experience necessary to review the broad range of projects under this program and did not present any conflicts of interest. Panel members and qualifications are described in Appendix C.

Meeting Preparation and Logistics

Prior to the meeting, the project team for each project being reviewed was asked to submit an 11-page Project Information Form that detailed project goals, purpose, and accomplishments to date. A standard set of specifications for preparing this document was provided by CRTD. These Project Information Forms were collected and provided to the Panel prior to the meeting.

Also in advance of the review meeting, CRTD gave the project teams a standard presentation template and set of instructions for the oral presentations they were to prepare for the Panel. All presentations were created in PowerPoint; the Panel was also given hard-copy handouts of these slides.

The Project Information Forms and presentations for all projects were provided to the Panel well in advance of the meeting to help them to better prepare for their roles.

Project Presentations, Evaluations, and Discussion

At the Carbon Sequestration Peer Review Meeting, presenters were held to a specific time limit (ranging from 45 to 60 minutes) to allow sufficient time for all presentations within the five-day meeting period. After each presentation, the project team participated in a question-and-answer session with the Panel for 30 to 40 minutes.

The Panel then spent 30 to 40 minutes evaluating the projects based on the presentation material. To start, each reviewer scored the project against a set of predetermined peer review criteria. The following nine criteria were used:

- Scientific and Technical Merit
- Existence of Clear, Measurable Milestones
- Utilization of Government Resources
- Technical Approach
- Rate of Progress
- Potential Technology Risks Considered
- Performance and Economic Factors
- Anticipated Benefits if Successful
- Technology Development Pathways

For each of these review criteria, individual Panel members scored each project as one of the following:

- Effective (5)
- Moderately Effective (4)
- Adequate (3)
- Ineffective (2)
- Results Not Demonstrated (1)

To facilitate the evaluation process, Leonardo Technologies, Inc. provided the Panel with laptop computers that were pre-loaded with Peer Review Criteria Forms for each project. The Panel then discussed the project for the purpose of defining project strengths, project weaknesses, recommendations, and a list of action items that the team must address. After scoring the projects on these criteria and discussing the project, the Panel provided written comments about each project.

APPENDIX B: MEETING AGENDA

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

FY10 Carbon Sequestration Peer Review

Sheraton Station Square

March 15-19, 2010

AGENDA

MONDAY, MARCH 15, 2010 - HASELTON ROOM

7:30 - 8:30 a.m.	Registration - **2ND FLOOR FOYER**
8:30 - 9:30 a.m.	Peer Review Panel Kick Off Meeting - Open to NETL and ASME staff only - Review of ASME Process - Michael Tinkleman/Ross Brindle, ASME - Role of Panel Chair - Daniel J. Kubek and Ian J. Duncan, ASME Peer Review Panel - Role of NETL - José Figueroa, NETL - Meeting logistics/completion of forms - Nicole Ryan/Justin Strock, TMS/NISC
9:30 - 10:15 a.m.	Overview - Open to NETL and ASME staff only - Carbon Sequestration Technology Manager – Sean Plasynski, National Energy Technology Laboratory (NETL)
10:15 - 10:30 a.m.	**BREAK - 2ND FLOOR FOYER**
10:30 - 11:15 a.m.	***01 - Project # ORD-FY10.ESD.1610251.612*** - Pre-combustion Solvents, Membranes, and Sorbents - Synthesis, Characterization, and Lab-Scale Performance Testing – *David Luebke*, **National Energy Technology Laboratory (NETL)**
11:15 - 11:45 a.m.	Q&A
11:45 - 12:25 p.m.	Discussion, evaluation, and written comments
12:25 - 1:25 p.m.	**Lunch (on your own)**
1:25 - 2:10 p.m.	***02 - Project # FWP-FE-10-002*** - High Temp Polymer-Based Membrane Systems for Pre-Combustion Carbon Dioxide Capture – *Kathryn A. Berchtold*, **Los Alamos National Laboratory (LANL)**
2:10 - 2:40 p.m.	Q&A
2:40 - 3:20 p.m.	Discussion, evaluation, and written comments
3:20 - 3:35 p.m.	**BREAK - 2ND FLOOR FOYER**
3:35 - 4:20 p.m.	***07 - Project # FWP-ESD09-056 Task 2*** - GEO-SEQ – *Barry M. Freifeld*, **Lawrence Berkeley National Laboratory (LBNL)**
4:20 - 4:50 p.m.	Q&A
4:50 - 5:30 p.m.	Discussion, evaluation, and written comments

TUESDAY, MARCH 16, 2010 - HASELTON ROOM

7:00 - 8:00 a.m.	Registration - **2ND FLOOR FOYER**

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Tuesday, March 16, 2010 - Haselton Room

8:00 - 8:45 a.m.	***12 - Project # NT42262*** - Basic Science of Retention Issues, Risk Assessment & Measurement, Monitoring, & Verification for Geologic CO_2 Sequestration (ZERT) – *Lee H. Spangler*, **Montana State University**
8:45 - 9:15 a.m.	Q&A
9:15 - 9:55 a.m.	Discussion, evaluation, and written comments
9:55 - 10:10 a.m.	**BREAK - 2ND FLOOR FOYER**
10:10 - 10:55 a.m.	***05 - Project # FWP-FE-10-001 Task 3*** - Systems Modeling & Science for Geologic CO_2 Sequestration – *Rajesh J. Pawar*, **Los Alamos National Laboratory (LANL)**
10:55 - 11:25 a.m.	Q&A
11:25 - 12:05 p.m.	Discussion, evaluation, and written comments
12:05 - 1:05 p.m.	**Lunch (on your own)**
1:05 - 1:50 p.m.	***06 - Project # FWP-ESD09-056 Task 5*** - Regional Modeling of Large-Scale Hydrologic Impact of CO_2 Storage – *Jens Birkholzer*, **Lawrence Berkeley National Laboratory (LBNL)**
1:50 - 2:20 p.m.	Q&A
2:20 - 3:00 p.m.	Discussion, evaluation, and written comments
3:00 - 3:15 p.m.	**BREAK - 2ND FLOOR FOYER**
3:15 - 4:00 p.m.	***03 - Project # ORD-GEC.1610251.600.B*** - Geologic Sequestration - Wellbore/Seal Integrity Project – *Brian Strazisar*, **National Energy Technology Laboratory (NETL)**
4:00 - 4:30 p.m.	Q&A
4:30 - 5:10 p.m.	Discussion, evaluation, and written comments

Wednesday, March 17, 2010 - Haselton Room

7:00 - 8:00 a.m.	Registration - **2ND FLOOR FOYER**
8:00 - 8:45 a.m.	***08 - Project # NT06642*** - Shallow Carbon Sequestration Demonstration Pilot – *Gary J. Pendergrass*, **City Utilities of Springfield**
8:45 - 9:15 a.m.	Q&A
9:15 - 9:55 a.m.	Discussion, evaluation, and written comments
9:55 - 10:10 a.m.	**BREAK - 2ND FLOOR FOYER**
10:10 - 10:55 a.m.	***09 - Project # FWP-FEW-0174 Task 3*** - Injection & Reservoir Hazard Mgmt: Fault Geomechanics and Integrated CO_2 Leakage Simulation Applied to Geologic Storage – *Walt McNab*, **Lawrence Livermore National Laboratory (LLNL)**
10:55 - 11:25 a.m.	Q&A
11:25 - 12:05 p.m.	Discussion, evaluation, and written comments
12:05 - 1:05 p.m.	**Lunch (on your own)**

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WEDNESDAY, MARCH 17, 2010 - HASELTON ROOM

1:05 - 1:50 p.m.	***10 - Project # FWP-FEW-0174 Task 2*** - Fresh Water Generation from Saline Formation-Pressured Carbon Storage – *Roger Aines*, **Lawrence Livermore National Laboratory (LLNL)**
1:50 - 2:20 p.m.	Q&A
2:20 - 3:00 p.m.	Discussion, evaluation, and written comments
3:00 - 3:15 p.m.	**BREAK - 2ND FLOOR FOYER**
3:15 - 4:00 p.m.	***11 - Project # NT04730*** - Carbon Sequestration Monitoring Activities – *Dorothy C. Yates*, **University of Wyoming**
4:00 - 4:30 p.m.	Q&A
4:30 - 5:10 p.m.	Discussion, evaluation, and written comments

THURSDAY, MARCH 18, 2010 - HASELTON ROOM

7:00 - 8:00 a.m.	Registration -**2ND FLOOR FOYER**
8:00 - 8:45 a.m.	***04 - Project # FWP-58159*** - Capture and Sequestration Systems Support: Basalt Formation Geologic Sequestration – *B. Peter McGrail*, **Pacific Northwest National Laboratory (PNNL)**
8:45 - 9:15 a.m.	Q&A
9:15 - 9:55 a.m.	Discussion, evaluation, and written comments
9:55 - 10:10 a.m.	**BREAK - 2ND FLOOR FOYER**
10:10 - 10:55 a.m.	***13 - Project # FWP-AACH-139*** - New Approach for Long Term Monitoring of Leaks from Geologic Sequestration – *Lucian Wielopolski*, **Brookhaven National Laboratory (BNL)**
10:55 - 11:25 a.m.	Q&A
11:25 - 12:05 p.m.	Discussion, evaluation, and written comments
12:05 - 1:05 p.m.	**Lunch (on your own)**
1:05 - 2:05 p.m.	***14 - Project # ORD-GEC.1610251.600.A*** - National Risk Assessment Program (NRAP) – *Grant Bromhal*, **National Energy Technology Laboratory (NETL)**
2:05 - 2:45 p.m.	Q&A
2:45 - 3:25 p.m.	Discussion, evaluation, and written comments
3:25 - 3:40 p.m.	**BREAK - 2ND FLOOR FOYER**
3:40 - 4:25 p.m.	***15 - Project # OSAP-CO2-EOR LCA*** - Assessing Net Storage Potential of CO_2-Flood Enhanced Oil Recovery: A Life Cycle Analysis Perspective – *Robert Dilmore*, **National Energy Technology Laboratory (NETL)**
4:25 - 4:55 p.m.	Q&A
4:55 - 5:35 p.m.	Discussion, evaluation, and written comments

FY10 Carbon Sequestration Peer Review
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FRIDAY, MARCH 19, 2010 - HASELTON ROOM

7:00 - 8:00 a.m.	Registration -**2ND FLOOR FOYER**
8:00 - 8:45 a.m.	***16 - Project # OSAP-41817.401.01.01*** - Assessment of Power Plants That Meet Proposed Greenhouse Gas Emission Performance Standards – *Eric Grol*, **National Energy Technology Laboratory (NETL)**
8:45 - 9:15 a.m.	Q&A
9:15 - 9:55 a.m.	Discussion, evaluation, and written comments
9:55 - 10:10 a.m.	**BREAK - 2ND FLOOR FOYER**
10:10 - 12:00 p.m.	Overall meeting Wrap-up 10 minutes/Reviewers x 8

APPENDIX C: PEER REVIEW PANEL MEMBERS

After reviewing the scientific areas and issues addressed by the 16 projects to be reviewed, the Center for Research and Technology Development (CRTD) staff and the American Society of Mechanical Engineers (ASME) Peer Review Executive Committee, in cooperation with the NETL project manager, identified the following areas of expertise as the required skill sets of the FY 2010 Carbon Sequestration Peer Review Panel:

- Geologic Sequestration
- Deep Reservoirs/Candidate Formations
- Demonstrations and Field Testing
- 3D Geologic Characterization
- GeoChemistry/Isotopic Composition/Brine
- Flow Properties of Aquifer Rock/Fractures
- Modeling (Waveform Performance/System)
- Well Data Collection
- Mixed-Phase carbon dioxide (CO_2) and Water
- Shallow Sequestration
- Gas Phase CO_2 Injection
- Site Characterization/Borings/Cores
- Well Permit Applications/Regulations
- Injection and Injection Rates
- Measurement, Monitoring, and Verification (MMV)
- Risk Assessment
- Enhanced Oil Recovery/Wellbore Integrity
- Near-Surface Carbon/CO_2 Detection MMV
- Solvents/Membranes/Sorbents
- Molecular Simulation/Ionic Liquids
- Carbon Capture in Terrestrial Systems
- Pre-Combustion Capture
- Economic Assessment
- Integrated Gasification Combined Cycle Plants
- Hydrological Impact/Groundwater

These required reviewer skill sets were then put into a matrix format and potential Panel members were evaluated on whether their expertise matched the required skill sets. This matrix also ensures that all the necessary skill sets are covered by the Panel. The Panel selection process also helps to ensure that the Panel represents the distinct perspectives of both academia and industry.

Considering the areas of expertise listed above, the CRTD carefully reviewed the résumés of all those who had served on prior ASME Review Panels for DOE (acknowledging the benefit of their previous experience in this peer review process) as well as a number of new submissions from DOE. It was determined that two individuals who had served on prior ASME Peer Review Panels were qualified to serve on the Carbon Sequestration Panel.

Appropriate résumés were then submitted to the Carbon Sequestration Peer Review Executive Committee for review. The following eight members were selected for the FY 2010 Carbon Sequestration (* indicates a prior Panel member):

Daniel J. Kubek*, Consultant—Panel Co-Chair

Ian Duncan, University of Texas at Austin—Panel Co-Chair

Neeraj Gupta, Battelle Memorial Institute

Gerald Hill, Southern States Energy Board

Michael Karmis, Virginia Polytechnic Institute

Ravi Prasad*, Consultant

John Rupp, Indiana University

Ed Steadman, University of North Dakota

Panel members reviewed pre-presentation materials prior to the meeting and spent five days at the meeting evaluating projects and providing comments. Panelists received an honorarium for their time as well as reimbursement of travel expenses. A brief summary of their qualifications follows.

FY 2010 Carbon Sequestration Peer Review Panel Members

Daniel J. Kubek, Panel Co-Chair

Mr. Kubek is a consultant specializing in synthesis gas and natural gas purification and separation. His clients include the Electric Power Research Institute – CoalFleet, for whom he provides technical guidance on integrated processes for gasification projects; and the Gasification Technologies Council, for which he serves as an advisor on technical issues related to gasification, particularly in the areas of hydrogen sulfide removal and carbon capture.

Mr. Kubek was with UOP LLC (a subsidiary of Union Carbide) for 18 years as senior technology manager. His career of technical expertise is based in separations technology and engineering. His primary work was in solvent absorption, molecular sieve thermal-swing adsorption, membrane permeation, and pressure-swing adsorption technologies, as applied to natural gas and synthesis gas processing. He was the process manager responsible for all process design packages for multiple gasification projects and served as development manager for UOP's gas processing business.

In 2005, Mr. Kubek was awarded UOP's Don Carlson Award for Career Technical Innovation. From 1996 to 2006 he served as UOP's representative to the Gasification Technologies Council's Board of Directors. He is the holder of eight Patents, and has co-authored 17 technical publications. Before joining UOP LLC, he spent 17 years with Union Carbide. Mr. Kubek received a B.S. degree in chemical engineering from Rutgers University and earned an M.S. in chemical engineering from Purdue University.

Ian Duncan, Ph.D., Panel Co-Chair

Ian Duncan has served as associate director and research scientist of the Bureau of Economic Geology (BEG) at the University of Texas at Austin since 2004. His research interests include scientific, environmental and public policy aspects of geologic storage such as CO_2 storage, compressed air storage, and natural gas storage. His current projects include: risk modeling and environmental impacts of CO_2 sequestration; environmental impact of biofuels; use of compressed air storage to achieve electric grid stability with high penetration of renewables; environmental impacts of shale gas fracking; and legal/regulatory issues related to CO_2 sequestration and energy production. Dr. Duncan was the science lead for the Texas FutureGen Team and was responsible for developing the data for the environmental impact volume for the two Texas FutureGen sequestration sites.

Dr. Duncan is also engaged in several research programs that are related to enhancing the viability of renewable energy resources including: geothermal energy from Gulf Coast geopressured reservoirs; assessing hybrid geothermal and solar energy; and hybrid wind-solar energy.

Since 2008, Dr. Duncan has testified to Congress three times on carbon sequestration, CO_2 enhanced oil recovery and protection of water resources. He also acted as Chair of the External Review Panel Burger CO_2 Injection Project, Battelle Memorial Institute (2009 to present); panel member of the Governor's External Review Panel Commonwealth of Pennsylvania CO_2 Sequestration (2008 to present); and conducted an external review of the CO_2 Sequestration Research Program Los Alamos National Laboratory (2007). Dr. Duncan has taught numerous short courses on CO_2 sequestration including monitoring, computer simulation, and geomechanics.

For 10 years, Dr. Duncan worked as scientist manager at the Virginia Department of Mines, Minerals, and Energy – Division of Mineral Resources. As a geology professor, he taught at Southern Methodist University, Dallas, and Washington University, St. Louis. He received a B.A. in earth sciences from Macquarie University in Australia and a Ph.D. in geology from the University of British Columbia.

Neeraj Gupta, Ph.D.

Dr. Gupta is a geologist at Battelle Memorial Institute; since 1996, he has been one of the leaders in Battelle's efforts to evaluate the feasibility of geologic storage of carbon dioxide in sedimentary formations. During this time, Dr. Gupta has played a key role in the formation of several public-private joint projects on geologic sequestration. Dr. Gupta developed and led a unique $8 million field project funded by major government and energy industry organizations at American Electric Power's Mountaineer Plant. Following completion of the site characterization work, this project is now transitioning into a larger effort involving geologic storage of CO_2 captured from the plant.

Dr. Gupta also leads a complex program of geologic storage demonstrations hosted by major energy companies as part of the Midwestern Regional Carbon Sequestration Partnership, a $23 million multi-client program led by Battelle. His current and previous work includes field investigations, regional hydrogeology, reservoir simulations of CO_2 storage, geochemical modeling and experiments, seismic assessments, cost and regulatory aspects, and development of CO_2 capture technologies.

Dr. Gupta also plays a significant technical advisory role on the Battelle's FutureGen project team. Dr. Gupta has had a major role in development of the research agenda for carbon management technologies through his extensive participation in government, private, and international dialogues. He has written more than 40 reports and papers on the subject and has been invited to present at numerous meetings and workshops, and has served on expert panels on the subject.

His educational and technical backgrounds include hydrogeology, geology, and geochemistry. Dr. Gupta earned a B.S. and M.S. in geology from Panjab University, India; a M.S. in geochemistry from George Washington University; and a Ph.D. in hydrogeology from the Ohio State University.

Gerald (Jerry) Hill, Ph.D.

Gerald (Jerry) Hill is senior technical advisor to the Southern States Energy Board (SSEB), a regional energy policy board composed of governors and state legislators from 16 states working with the U.S. Department of Energy on carbon capture and sequestration research. Dr. Hill is active in research related to clean coal technologies, carbon sequestration, and water-for-energy.

Dr. Hill is coordinating technical aspects of climate change projects for the SSEB. In 2003 SSEB entered into a cooperative agreement with the U.S. Department of Energy to lead the Southeastern Regional Carbon Sequestration Partnership. The Southeast partnership currently is conducting four Phase II small-scale CO_2 injection experiments and has initiated activities for two Phase III large-scale CO_2 injection experiments.

From 2005 to 2006, Dr. Hill served as a consultant to the University of Texas at Austin on the FutureGen Texas team. He participated in the evaluation of 15 potential host sites and in the development of two FutureGen project proposals, with emphasis on the integration of the FutureGen reference plant with site-specific transportation and sequestration options. Dr. Hill has over 30 years experience with the petroleum and electric utility industries. He earned a B.S. and M.S. in environmental science and an M.S. and Ph.D. in civil engineering from the University of Iowa.

Michael Karmis, Ph.D.

Dr. Michael Karmis is the Stonie Barker Professor of the Department of Mining and Minerals Engineering, as well as the Director of the Virginia Center for Coal and Energy Research (VCCER) at Virginia Polytechnic Institute. The VCCER was established by the Virginia Legislature to support research, educational, and public policy programs in coal and energy in the Commonwealth. The VCCER is a research partner of the Southeast Carbon Sequestration Regional Partnership, one of the seven regional partnerships established by National Energy Technology Laboratory and managed by the Southern States Energy Board.

Dr. Karmis' expertise is in the areas of rock mechanics, health and safety, carbon sequestration, and the sustainable development of energy and mineral resources. He has authored more than 150 scientific papers, reports, *Proceedings* volumes, and textbooks, and has directed 45 major research projects.

Dr. Karmis has been active in consulting with the minerals industry, consulting companies, government organizations, and legal firms. He served as the 2002 president of the Society for Mining, Metallurgy, and Exploration (SME) and the 2008 president of the American Institute of Mining, Metallurgical, and Petroleum Engineers, one of the five founding engineering societies. Since 2003, he serves as the alternate to the Governor of Virginia on the Southern States Energy Board. He is a distinguished member of the SME, a Fellow of the Institute of Quarrying, and a Fellow of the Institute of Materials, Minerals, and Mining. He has received numerous recognitions and awards by major scientific, professional, and industrial organizations.

Previously, Karmis was a recipient of the National Stone Association Professor of the Year award for significant contributions to the education of young men and women preparing for careers in the mineral aggregates mining industry. The award recognizes teaching excellence, dedication, motivation of students, and national contributions to teaching; this is his fourth Certificate of Teaching Excellence. Dr. Karmis has bachelor's and doctorate degrees from Strathclyde.

Ravi Prasad, Ph.D.

Dr. Prasad of Helios-NRG, LLC and formerly a corporate fellow of Praxair Inc., has 60 U.S. patents and broad industrial experience in developing and commercializing new technologies, launching technology programs ($2–$50 million), supporting business development, building cross-functional teams, and setting up joint development alliances. He is a founding member of an alliance involving Praxair, British Petroleum, Amoco, Phillips Petroleum, Statoil, and Sasol to develop ceramic membrane synthesis gas (syngas) technology for gas-to-liquid processes. He established and led programs for ceramic membrane oxygen technology; co-developed proposals to secure major DOE programs worth $35 million in syngas and $20 million in oxygen; identified novel, solid-state oxygen generation technology; and conceived and implemented a coherent corporate strategy in nanotechnology. He has championed many initiatives in India, including small on-site hydrogen plants, small gasifiers, and aerospace business opportunities; and developed implementation plans resulting in a new research and development center in Shanghai. Dr. Prasad has a B.S. in mechanical engineering from the Indian Institute of Technology in Kanpur, India, and an M.S. and Ph.D. in mechanical engineering and chemical engineering from the State University of New York, Buffalo, New York.

John Rupp

John Rupp is the assistant director for research and section head of subsurface geology at Indiana University's Indiana Geological Survey. He specializes in energy issues related to petroleum, coal, and natural gas, including subsurface geology, unconventional reservoir analysis, and carbon sequestration. Current research topics include subsurface stratigraphy, reservoir analysis, and operations development in the deep subsurface of the Illinois Basin for carbon sequestration;

and the evaluation of the coal-bed methane for gas shale-enhanced production using CO_2 injection. Mr. Rupp serves as the project director for Indiana on two of the DOE Regional Carbon Sequestration Partnerships: the seven-state Midwest Regional Carbon Sequestration Partnership and the three-state Midwestern Geological Sequestration Consortium. He also co-chaired the 2008 Indiana Carbon Capture and Storage Summit. He has served on external review panels for research activities of the Department of Energy’s National Energy Technology Laboratory and the Advanced Research Project Agency-Energy.

Mr. Rupp is a member of the American Association of Petroleum Geologists, the Indiana Academy of Science, and also serves on the Governors’ Task Force on Carbon Sequestration Legislation. He earned a B.S. in geology from the University of Cincinnati and a M.S. in geology from the Eastern Washington University.

Ed Steadman

Ed Steadman is a Senior Research Advisor at the University of North Dakota’s Energy and Environmental Research Center, where he is responsible for directing a multidisciplinary team of researchers on a carbon sequestration project in which detailed inventories of CO_2 sources, geologic and terrestrial sinks, and sequestration infrastructure were made; CO_2 capture and separation technologies were identified; monitoring, verification, and accounting technologies and permitting requirements were investigated; and the most promising opportunities for carbon sequestration in nine states and four Canadian provinces were defined. Other responsibilities include development, marketing, management, and dissemination of commercially oriented research and development of programs focused on the environmental effects of power and natural resource production.

Mr. Steadman currently serves as the program manager for the Plains CO_2 Reduction Partnership, one of seven regional partnerships funded by the U.S. Department of Energy's National Energy Technology Laboratory Regional Carbon Sequestration Partnership Program, to assess the technical and economic feasibility of capturing and storing (sequestering CO_2 emissions from stationary sources in the northern Great Plains and adjacent area). Mr. Steadman's principal areas of expertise are carbon sequestration, watersheds, sustainable development, chemical transformations during coal combustion, and materials science. He holds an M.A. in geology from the University of North Dakota and a B.S. in geology from the University of Pennsylvania-Edinboro.

APPENDIX D: PEER REVIEW CRITERIA FORM

PEER REVIEW CRITERIA FORM

U. S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY
FY10 CARBON SEQUESTRATION
PEER REVIEW

March0 15 – 19, 2010

Project Title:	
Performer:	
Presenter:	
Name of Peer Reviewer:	
Date of Review:	

The following pages contain the criteria used to evaluate each project. The criteria have been grouped into three (3) major categories: (1) **Approach and Progress**; (2) **Project Merit**; and (3) **Deployment Considerations**. Additionally, each criterion is accompanied by multiple characteristics to further define the topic.

The Reviewer is expected to provide a **rating** and **substantive comments** which support that rating for each criterion. Please note that if a rating of ***"Results Not Demonstrated"*** is selected, **justifying comments must be included**. To assist with determining the criterion rating, adjectival descriptions of those ratings are provided below.

RATING CRITERIA DEFINITIONS	
Effective	**Effective** projects set ambitious goals, achieve results, are well-managed and enhance the likelihood of meeting program goals and objectives.
Moderately Effective	In general, a project rated **Moderately Effective** has set ambitious goals and is well-managed, and is achieving results. Better results could be realized by focusing on key technical issues, more efficient use of resources, and improvements in overall management.
Adequate	**Adequate** describes a project that needs to set more ambitious goals, achieve better results, improve accountability or strengthen its management practices.
Ineffective	**Ineffective** projects are unable to achieve results due to a lack of clarity regarding the project's purpose or goals, poor management, or some other significant weakness (e.g., technical problem).
Results Not Demonstrated	**Results Not Demonstrated** indicates that a project has not been able to develop acceptable performance goals or collect data to determine whether it is performing.

Page 1 of 5

PEER REVIEW RATING CRITERIA

Please evaluate the project against each of the 9 criterion listed below. Definitions for these 9 criteria are provided on page 4. For each criterion, select the appropriate rating by typing an "X" in the applicable cell. Definitions for the five ratings criteria are provided on page 1.

NOTE: If you rate any criterion as "Results Not Demonstrated," a justification for this rating is required. Please include your justification in the box at the end of this table.

CRITERION		RATING CRITERIA				
(Criterion Definitions, refer to Page 4)		(Rating Criteria Definitions, refer to Page 1)				
		Effective	Moderately Effective	Adequate	Ineffective	Results Not Demonstrated*
PROJECT OVERVIEW						
1	**Scientific and Technical Merit**					
2	**Existence of Clear, Measurable Milestones**					
3	**Utilization of Government Resources**					
TECHNICAL DISCUSSION						
4	**Technical Approach**					
5	**Rate of Progress**					
6	**Potential Technology Risks Considered**					
7	**Performance and Economic Factors**					
TECHNOLOGY BENEFITS						
8	**Anticipated Benefits, if Successful**					
9	**Technology Development Pathways**					
*Please explain why the project was rated "Results Not Demonstrated" for a particular criterion.						

Page 2 of 5

COMMENTS

Please provide your comments for each of the areas in the blocks below. Please substantiate your comments (i.e., facts on why you are making the statement). General statements without explanation (e.g., great project) are not sufficient. Please avoid any use of clichés, colloquialisms or slang.

Strengths:
Weaknesses:
Recommendations:
Action Items:
General Comments:

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CRITERION DEFINITIONS

PROJECT OVERVIEW

1: Scientific and Technical Merit

- The underlying project concept is scientifically sound.
- Substantial progress or even a breakthrough is possible.
- A high degree of innovation is evident.

2: Existence of Clear, Measurable Milestones

- At least two measureable milestones per budget period exist.
- Milestones are quantitative and clearly show progression towards project goals.
- Each milestone has a title, planned completion date and a description of the method/process/measure used to verify completion.

3: Utilization of Government Resources

- Research team is adequate to address project goal and objectives.
- Sound rationale presented for teaming or collaborative efforts.
- Equipment, materials, and facilities are adequate to meet goals.

TECHNICAL DISCUSSION

4: Technical Approach

- Technical approach is sound and supports stated project goal and objectives.
- A thorough understanding of potential technical challenges and technical barriers is evident.

5: Rate of Progress

- Progress to date against stated project goal, objectives, milestones, and schedule is reasonable.
- Continued progress against possible technical barriers is likely.
- There is a high likelihood project goal, objectives, and expected outcomes and benefits will be achieved.
- The budget is on track to achieve project goal and objectives.

6: Potential Technology Risks Considered

- Potential risks to the environment or public associated with widespread technology deployment have been considered.
- Project risks are identified and effective measures to address and mitigate these risks, including potential technical uncertainties and barriers, are presented.
- Scientific risks are within reasonable limits.

7: Performance and Economic Factors *

- Appropriate technology cost and performance assessments are conducted consistent with the level of technology development.
- Implementation cost estimates, if warranted, are sensible given uncertainties.
- There is a high likelihood of meeting ultimate DOE cost and performance goals.

TECHNOLOGY BENEFITS

8: Anticipated Benefits, if Successful

- There exist clear statements of potential benefits if research is successful.
- Technologies being developed can benefit other programs.
- Project will make a significant contribution towards meeting near- and long-term program cost and performance goals.

9: Technology Development Pathways *

- Researchers know and can describe a "real world" application and adequately discuss requirements (additional research, potential partners, and resources) for the next level of technology development.
- Market analyses, if appropriate, indicate the technology being developed is likely to be implemented if research is successful.
- Potential barriers to commercialization have been identified and addressed, if appropriate.

* Additional details to be considered for Criterion 7 (Performance and Economic Factors) and 9 (Technology Development Pathways) for specific Technology Development Stages are described on the next page.

Page 4 of 5

TECHNOLOGY DEVELOPMENT STAGES FOR ECONOMIC ANALYSIS & TECHNOLOGY DEVELOPMENT PATH

In past Peer Reviews, Peer Review Panelists have had difficulty scoring the "Economic Analysis" and "Technology Development Path" criterions, because the rating criteria were not specific to the stage of technology development. Research, Development, and Demonstration projects can be categorized based on the level of technology maturity. Listed below are five (5) technology development categories of RD&D projects managed by the National Energy Technology Laboratory. These technology maturation categories are often termed "stages," which provide a basis for establishing a rational and structured approach to decision-making and identifying performance criteria that must be met before proceeding to a subsequent stage of development.

Fundamental Research—Explores and defines technical concepts or fundamental scientific knowledge; laboratory-scale; traditionally but not exclusively the province of academia.

Applied Research—Laboratory- or bench-scale proof of the feasibility of multiple potential applications of a given fundamental scientific discovery.

Prototype Testing—Prototype technology development and testing, either in the laboratory or field; predictive modeling or simulation of performance; evaluation of scalability.

Proof-of-Concept—Pilot-scale development and testing of technology or process; field testing and validation of technology at full-scale, but in a manner that is not designed or intended to represent a long-term commercial installation.

Major Demonstration—Commercial-scale demonstration of energy and energy-related environmental technologies; generally a first-of-a-kind representation of a long-term commercial installation.

Table 1 describes economic analysis and technology development sub-criteria for each of the five technology development stages. These sub-criteria are examples of the types of information that is typically determined in technology research and development projects.

Please note that the Economic Analysis and Technology Development Path are examples of the types of information that should be provided for the projects being reviewed. Projects are not expected to address all sub-criteria for a given Technology Development Stage, but should address at least one of them.

Table 1. Economic Analysis and Technology Development Sub-Criteria

Technology Development Stage	Economics Analysis Sub-Criteria	Technology Development Path Sub-Criteria
Fundamental Research	• Material costs available • Potential cost benefits over conventional systems identified	• Scientific feasibility proven • Application(s) considered • Potential technology developers identified
Applied Research	• Component or sub-system costs estimated • First-order cost-benefit analysis available • Material and energy balances calculated	• Conceptual process proposed • Potential applications well defined • Process feasibility established
Prototype Testing	• Conceptual process costs developed • Market analysis completed • Risk assessment completed	• Process test data available • Engineering scale-up data developed • Optimum operating conditions identified
Proof-of-Concept	• Process contingency costs identified • Full-scale process costs, including O&M calculated • Full-scale installation costs developed	• Major technology components thoroughly tested and evaluated • Technology demonstration plans firmly established • Major component optimization studies performed
Major Demonstration	• Installation costs determined	• Business and commercialization plans developed

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APPENDIX E: CARBON SEQUESTRATION PROJECT SUMMARIES

Presentation ID Number	Project Number	Title
01	ORD-FY10.ESD.1610251.612	Pre-combustion Solvents, Membranes, and Sorbents - Synthesis, Characterization, and Lab-Scale Performance Testing
02	FWP-FE-10-002	High Temperature Polymer-Based Membrane Systems for Pre-Combustion Carbon Dioxide Capture
03	ORD-GEC.1610251.600.B	Geologic Sequestration - Wellbore/Seal Integrity Project
04	FWP-45502/FWP-58159	Sequestration of CO_2 in Basalt Formations
05	FWP-FE-10-001 Task 3	Systems Modeling & Science for Geologic CO_2 Sequestration
06	FWP-ESD09-056 Task 5	Regional Modeling of Large-Scale Hydrologic Impact of CO_2 Storage
07	FWP-ESD09-056 Task 2	GEO-SEQ
08	DE-NT0006642	Shallow Carbon Sequestration Demonstration Pilot
09	FWP-FEW-0174 Task 3	Injection & Reservoir Hazard Management: Fault Geomechanics and Integrated CO_2 Leakage Simulation Applied to Geologic Storage
10	FWP-FEW-0174 Task 2	Fresh Water Generation from Saline Formation-Pressured Carbon Storage
11	DE-NT0004730	Carbon Sequestration Monitoring Activities
12	DE-FC26-04NT42262	Basic Science of Retention Issues, Risk Assessment & Measurement, Monitoring, & Verification for Geologic CO_2 Sequestration (ZERT)
13	FWP-AACH-139	New Approach for Long-term Monitoring of Leaks from Geologic Sequestration
14	ORD-GEC.1610251.600.A	National Risk Assessment Program (NRAP)
15	OSAP-CO2-EOR LCA	Assessing Net Storage Potential of CO_2-Flood Enhanced Oil Recovery: A Life Cycle Analysis Perspective
16	OSAP-41817.401.01.01	Assessment of Power Plants that Meet Proposed Greenhouse Gas Emission Performance Standards

01: ORD-FY10.ESD.1610251.612

Project Number	**Project Title**			
ORD-FY10.ESD.1610251.612	Pre-combustion Solvents, Membranes, and Sorbents - Synthesis, Characterization, and Lab-Scale Performance Testing			
Contacts DOE/NETL Project Mgr.	**Name** David Luebke	**Organization** NETL–Office of Research and Development	**Email** David.Luebke@netl.doe.gov	
Principal Investigator	David Luebke	NETL–Office of Research and Development	David.Luebke@netl.doe.gov	
Partners	Bob Enick, University of Pittsburgh Badie Morsi, University of Pittsburgh			
Stage of Development				
__ Fundamental	X Applied R&D	__ Proof of Concept	__ Prototype Testing	__ Demonstration

Technical Background:

Historically, the majority of NETL's in-house, precombustion carbon dioxide (CO_2) capture work has consisted of collaborations with universities focused on performance screening, rather than materials development. In the "Solvents for CO_2 Capture" project, commercially available ionic liquids were tested in a large bench-scale reactor at the University of Pittsburgh (Pitt). During this testing, ideal solvent characteristics were defined and a design was prepared for a high-temperature solvent capture system. The configuration of the autoclave unit at Pitt allowed measurement of both CO_2 capture capacity and mass-transfer coefficients in mixtures containing multiple gases. These results were unique in the literature and demonstrated that mass transfer in ionic liquids is not critically limited by viscosity, as had been previously suggested. Testing also showed that the class of ionic liquids tested was not vulnerable to poisoning by hydrogen sulfide (H_2S) and could potentially be used as capture solvents for both CO_2 and H_2S in much the same manner as Selexol. Unfortunately, the work at Pitt also revealed that the commercially available ionic liquid materials were not competitive in capacity with Selexol, and new, more effective ionic liquid solvents will have to be located if the technology is to be successful. A major question about the solvent capture technology that would have been addressed if the work had continued was the fate of the synthesis gas (syngas) water. However, since the class of ionic liquids being studied could not meet performance requirements and the solubility of water in ionic liquids varies widely among different materials, it was not thought to be a prudent use of experimental resources to make those measurements. Once a new high-capacity ionic liquid is selected, water solubility and the heat of the solution will be measured. If necessary, mitigation techniques such as a hydrophobic membrane contactor or the optimization of the ionic liquid for water desorption at a temperature higher than that of the CO_2 may be introduced to reduce water removal from the syngas.

The "Membranes for CO_2 Separation" project examined the performance of membranes made from ionic liquids synthesized under a Cooperative Research and Development Agreement at the University of Notre Dame. The project successfully tested supported ionic liquid membranes at temperatures as high as 300°C, a major improvement over other supported liquid membrane technologies.

Further advances in the membrane technology incorporated functionalities into the ionic liquid that chemically interact with CO_2 and allow the membranes to maintain selectivity at higher temperatures through facilitated transport. Though steady progress has been made in the membrane work, the speed of ionic liquid improvement must increase and practical membrane supports must be developed.

The heart of the work discussed here is an ionic liquid capture technology development program that integrates Monte Carlo and molecular dynamics simulation, ionic liquid and polymer synthesis, rapid characterization, polymer fabrication, and performance testing. The research has been divided into the following five tasks:

TASK 1: MOLECULAR MODELING (THIS TASK IS EVALUATED UNDER A SEPARATE REVIEW)

The computational effort will test existing force fields in Monte Carlo simulations and evaluate their ability to predict gas solubilities in ionic liquids. The results of these experiments may serve as a rough predictive tool, but it will likely be necessary to develop force fields designed specifically for the ionic liquids in order to achieve truly accurate results. If this process is necessary, appropriate force fields will be constructed by *ab initio* calculations. These force fields will then be used in Monte Carlo simulations, and the whole process will be experimentally validated. Molecular dynamics simulations will also be used to model the transport properties of ionic liquids. When validation is complete, the tools developed should make it possible to tie molecular structures to macroscopic performance properties such as CO_2 capture capacity and permeability. These tools and the insights developed through the collaboration will then be used to suggest potential ionic liquids for experimental evaluation.

TASK 2: POLYMER AND IONIC LIQUID SYNTHESIS

A major shortcoming of NETL's efforts in CO_2 capture has arisen from the lack of ability to synthesize new materials on site. This deficiency limits carbon capture and storage (CCS) researchers to the use of commercial materials or proprietary materials owned by others. A safety permit has been completed and equipment has been procured for a polymer synthesis laboratory to support the CO_2 capture effort. The laboratory will be set up and its capacity will be expanded to include ionic liquid synthesis. With these capabilities, the laboratory will be able to serve as a bridge between computational and experimental efforts. New materials suggested by the computational effort can be synthesized for characterization and performance testing, and the integration of synthetic expertise into the ionic liquid development program is already generating new ideas for improved capture technologies.

TASK 3: IONIC LIQUID SOLVENTS

With the completion of the University of Pittsburgh work, ionic liquids have been established as feasible high-temperature solvents, but current materials do not meet capacity requirements. To move toward practical ionic liquid solvents, new materials must be developed with improved physical solubility for CO_2. The first goal will be to supply experimental validation to the molecular modeling described above. Using the previously developed ideal solvent parameters, ionic liquid testing experience, and validated molecular modeling, the project team will select candidate ionic liquids. The liquids will be synthesized on site, and isotherms and kinetic coefficients will then be measured in a volumetric gas sorption apparatus. The most promising candidates will be examined in multiple cycles, followed by further modeling to examine water and contaminant solubilities. The overall goal for fiscal year 2010 (FY2010) is to produce a list of thoroughly screened candidate ionic liquids for evaluation in the presence of water and contaminants, including a complete systems analysis. NETL will then be positioned to move forward with choosing an industrial partner for further ionic liquid solvent technology development.

TASK 4: IONIC LIQUID MEMBRANES

Recent advances in the membrane work have revealed ionic liquids well within the performance requirements that have been suggested for both natural gas sweetening and flue gas capture. However, additional ionic liquid development is necessary to improve membrane performance at the elevated temperatures necessary for precombustion capture. To address this need, the membrane project will make use of work done on molecular modeling and solvents to select probable candidates and develop the synthesis capability to prepare novel ionic liquids. New ionic liquids will continue to be tested in the existing membrane performance systems. The existing ionic liquids and those to be developed will require practical support materials that effectively contain the ionic liquid under realistic process conditions without significantly decreasing performance properties. A safety permit for a fiber spinning apparatus has been designed and initiated, and that system will be constructed in early FY2010, with membrane support development to begin immediately. New hollow fiber membrane supports will be characterized and evaluated for performance in existing membrane systems. The goal for FY2010 is to develop practical membranes for fuel gas, flue gas, and natural gas sweetening based on the ionic liquids already tested, and to develop improved ionic liquids for use in future membrane generations. After these objectives are met, NETL should be in an excellent position to enter into a development agreement with an industrial partner to scale up the membrane modules in FY2011.

TASK 5: PRODUCING HIGH-PRESSURE HYDROGEN (H_2) AND HIGH-PRESSURE CO_2 STREAMS FROM A HIGH-PRESSURE CO_2-H_2 MIXTURE WITH NOVEL CO_2-PHILIC ABSORBENTS

Liquid Oligomeric Solvents. Previous work with molecular modeling tools (e.g., COSMOtherm) and experimental techniques (e.g., determination of bubble point loci at 25°C) established that several CO_2-philic oligomers may be able to serve as solvents for CO_2 capture via gas absorption at low temperature. These oligomers include polypropyleneglycol dimethylether (PPGDME), polypropyleneglycol diacetate (PPGDAc), polydimethyl siloxane (PDMS), and perfluoropolyethers (PFPE). In the upcoming year, further work is proposed to determine the viscosity of each of these oligomers over the 25°C–100°C range. Synthesis is also being attempted on polyacetoxy oxetane (PAO), an oligomer designed with molecular modeling tools that may be an excellent CO_2 solvent. Non-sampling techniques will be used to determine the solubility of CO_2 in some of the more promising solvents, such as PPGDME or PPGDAc, over a wider temperature range covering both absorption and desorption conditions (25°C–100°C). Polyethyleneglycol dimethylether (PEGDME), a widely used physical solvent for CO_2 absorption, will be used as the baseline or control solvent in this study of liquid solvents. Testing in a new high-pressure phase equilibrium apparatus at the Pittsburgh NETL site will enable the use of sampling techniques to determine the mixed-gas solubility of the most promising solvent when exposed to a 50:50 (mol%) mixture of CO_2 and H_2. These results will determine if the solvent is well suited for the selective absorption of CO_2.

Solid Solvents. Previous work identified several CO_2-philic solids, including tritertbutyl benzene (TTBB), tritertbutyl phenol (TTBP), glucose pentaacetate (GlPA), galactose pentaacetate (GaPA), and maltose octaacetate (MOA), that melt in the presence of dense CO_2, absorb large amounts of CO_2, and release all of the CO_2 during regeneration via a modest pressure reduction as the compound reverts to the solid phase. TTBP has been purified and is now being examined with non-sampling techniques to determine whether TTBP will melt in the presence of a 50:50 CO_2-H_2 mixtures. In the upcoming year, non-sampling techniques will be used to determine which of these compounds (i.e., TTBP, GlPA, GaPA, and/or MOA) will melt in the presence of a 50:50 CO_2-H_2 mixture. Once the conditions for attaining a liquid solvent are ascertained, sampling techniques will be used at the Pittsburgh NETL site to determine the mixed-gas solubility of CO_2 and H_2 in one of these novel-phase change-solvents when exposed to a 50:50 (mol%) mixture of CO_2 and H_2. This testing will enable to project team to determine whether the compound is well suited for the selective absorption of CO_2 over H_2.

Relationship to Program:

This project will support important membrane advances within the CO_2 capture pathway of the NETL Carbon Sequestration Program. The project will develop materials for CO_2 capture applications, focusing on CO_2-selective membranes and solvents. Successful completion of the project will produce materials which, once incorporated into capture technologies, will result in the ability to capture CO_2 from coal gasification systems with less than a 10% increase in the cost of energy services. Materials produced through this project may also be applicable in areas such as flue-gas capture of CO_2 and natural gas sweetening.

Primary Project Goal:

This project seeks to decrease CO_2 capture costs through the development of robust solvent, sorbent, and membrane technologies that are able to efficiently capture CO_2 at elevated temperatures in the presence of common fuel gas contaminants, while also retaining water vapor and H_2 for expansion in the turbine.

The primary project goal is to develop solvent and membrane CO_2 capture technologies capable of meeting the Carbon Sequestration Program goal of capturing 90% of the CO_2 emissions from integrated gasification combined cycle power plants and securing 99% of those emissions for more than 100 years, while increasing the cost of energy services produced in the plants by less than 10%.

Objectives:

POLYMER AND IONIC LIQUID SYNTHESIS TASK

1. *Completion of Synthesis Laboratory Setup.* Preliminary work such as the installation and calibration of equipment, cleaning of laboratory space, organization of glassware and consumables, and development of laboratory procedures will be completed prior to operation.
2. *Design and Synthesis of Ionic Liquids.* Based on literature and modeling data, novel ionic liquids with characteristics desirable in CO_2-selective membrane and solvent applications will be designed and synthesized in the new facility.
3. *Design and Synthesis of Monomers.* Based on literature and modeling data, a library of monomers suitable for inclusion in polymers with characteristics desirable in CO_2 membrane applications will be designed and synthesized in the new facility.
4. *Polymerization and Copolymerization.* The functional monomers will be polymerized and copolymerized at various ratios with a second inexpensive monomer. The

project goal is to create a material with the desired properties at the least possible expense.

5. *Polymer and Ionic Liquid Characterization.* The physical and chemical properties of materials developed in the laboratory will be characterized using techniques including Fourier transform infrared (FTIR) and ultraviolet-visible (UV-Vis) spectroscopy, nuclear magnetic resonance (NMR), gel permeation chromatography (GPC), direct memory access (DMA), and Brunauer-Emmett-Teller (BET) theory.

IONIC LIQUID SOLVENTS TASK

1. *Completion of Installation and Shakedown of Volumetric Sorption System.* A Sievert-type isotherm apparatus has been purchased and will be set up in the existing laboratory space. Gas sorption isotherms produced in the instrument will be benchmarked against those available from literature.
2. *Validation of Molecular Modeling Results.* Isotherms for CO_2 and H_2 will be measured for an ionic liquid; results will be compared to those predicted in the Monte Carlo simulations.
3. *Characterization of Candidate Ionic Liquids.* A series of ionic liquids suggested by molecular modeling studies and previous testing experience will be characterized for CO_2 and H_2 solubility, transport properties, and stability to enable the selection of materials most suited for further testing as fuel gas solvents and membranes.

IONIC LIQUID MEMBRANES TASK

1. *Examination of the Effect of Other Common Fuel Gas Components***.** The effect of gases such as water vapor and methane on membrane performance will be examined in order to determine the potential robustness of promising ionic liquid membranes.
2. *Completion of Construction and Shakedown of Hollow-Fiber Spinning System.* A system will be constructed that is capable of producing practical, polymeric-fiber membrane materials containing ionic liquids.
3. *Hollow-Fiber Membrane Performance Testing.* Membranes produced in the spinning system from well-studied and novel ionic liquids will be characterized for CO_2 and H_2 permeability, selectivity, and stability in mixed-gas performance systems.
4. *Metal Organic Framework Mixed Matrix Membrane Testing.* Membranes produced in collaboration with the Korea Institute of Earth Research that incorporate metal organic frameworks into polymer matrices will be characterized for CO_2 and H_2 permeability, selectivity, and stability in mixed-gas performance systems

PRODUCING HIGH-PRESSURE H_2 AND HIGH-PRESSURE CO_2 STREAMS FROM A HIGH-PRESSURE CO_2-H_2 MIXTURE WITH NOVEL CO_2-PHILIC ABSORBENTS TASK

1. *Completion of Modification to Gas-Liquid Phase Behavior Apparatus.* Modifications to an existing system to allow the generation of three-component phase diagrams for solvents, CO_2, and H_2 will be completed.
2. *Three-component Testing of Oligomeric and Phase-Change Materials.* Phase diagrams will be experimentally developed for both classes of materials in order to determine how selectively CO_2 is captured in the presence of H_2.

02: FWP-FE-10-002

Project Number	**Project Title**			
FWP-FE-10-002	High Temperature Polymer-Based Membrane Systems for Pre-Combustion Carbon Dioxide Capture			
Contacts	**Name**	**Organization**	**Email**	
DOE/NETL Project Mgr.	Robie Lewis	NETL – Fuels Division	Robie.Lewis@netl.doe.gov	
Principal Investigator	Kathryn A. Berchtold	Los Alamos National Laboratory	berchtold@lanl.gov	
Partners				
Stage of Development				
__ Fundamental	X Applied R&D	__ Proof of Concept	__ Prototype Testing	__ Demonstration

Technical Background:

Los Alamos National Laboratory (LANL) performs applied research and development in carbon dioxide (CO_2) capture in support of the NETL Carbon Sequestration Program. The goal of this work is to execute the enabling science that will help lead to large-scale deployment of CO_2 capture technology as part of DOE's program to mitigate anthropogenic emission of CO_2, focusing specifically on the utility sector. This project is aimed at the continued development and demonstration of LANL-developed membrane-based precombustion hydrogen purification/carbon capture materials, technologies, and separation schemes.

Separating and capturing carbon dioxide from mixed gas streams is a first and critical step in carbon sequestration. To be technically and economically viable, a successful separation method must be applicable to industrially relevant gas streams at realistic temperatures and pressures, and must also be compatible with large gas volumes. While the separation of CO_2 from process streams is readily accomplished via standard separation techniques such as amine scrubbing and pressure-swing adsorption, the effectiveness of these current technologies for separating CO_2 is limited. These techniques require low temperatures and produce a low-pressure CO_2 stream, resulting in a significant energy penalty for separating CO_2. In contrast, polymer-based membrane separations are less energy intensive, requiring no phase change in the process, and typically provide low-maintenance operations. Polymer membranes have been used successfully in a number of industrial applications, including high-purity nitrogen production, gas dehydration, acid-gases removal, and hydrogen recovery from process streams for recycle. However, successful use of a polymer membrane in a synthesis gas (syngas) separation requires a membrane that is thermally, chemically, and mechanically stable at high temperature and high pressure in the presence of chemically challenging syngas components. Unfortunately, the commercially available polymeric materials currently employed in separation applications are not stable in these demanding environments to the degree required. Current membrane materials are often subject to chemical degradation by minor components in the process stream, a problem that is exacerbated by elevated temperature. Additionally, as the glass transition temperature of the polymer is approached, membrane selectivity is significantly reduced, and flux decline due to membrane compaction (creep) is increased. Consequently, there is a compelling need for membrane materials and capture systems based on those materials that can operate under extreme environmental conditions for extended periods of time while providing a level of performance that is economically sustainable by the end user.

Inorganic membranes, which include zeolites, carbon molecular sieves, and selective surface-flow membrane, serve as alternatives to polymer membranes. These membranes currently suffer from a lack of reproducibility, densification due to humidity and elevated temperatures, and high-cost fabrication. Given these limitations, mixed-matrix membranes and cross-linked membranes have been suggested as viable development pathways. Mixed-matrix membranes are often composed of carbon molecular sieves or zeolites embedded in a polymer matrix. Although permeabilities and selectivities have been increased above the traditional upper bound for polymers, application temperatures are still limited by the polymer matrix. Alternatively, cross-linked membranes can reduce the plasticization effects at elevated pressures and can increase membrane selectivity; however, permeability is typically adversely affected. Hence, the development of high-performance polymer membranes remains an attractive and viable engineering approach to filling the critical need for high-temperature membrane separations.

Through this work, benzimidazole-based polymer chemistries have been identified as exceptional candidates for the capture of CO_2 and the purification of hydrogen from coal-derived syngas streams. These materials possess excellent chemical resistance, very high glass transition temperatures (approximately 450°C), good mechanical properties, and an appropriate level of processability. Much of the initial work involving this class of selective barrier materials has focused on understanding the permselectivity character and durability of these materials under industrially relevant conditions. These efforts have led to the realization of polybenzimidazole (PBI)-based membrane chemistries, structures, deployment platforms, and sealing technologies that achieve the aforementioned critical combination of high permselectivity and durability at elevated temperatures (up to 400°C, the highest reported viable operating temperature of a polymer-based membrane). The project team’s results also indicate that the developed materials not only function at significantly higher temperatures (>400°C) than current commercially available polymeric membranes (<150°C), but also provide improved performance while exhibiting long-term temperature stability, sulfur tolerance, and durability over a broad range of industrially relevant operating conditions. Systems and economic analyses combined with in- and out-of-laboratory testing established the technical viability of these materials and indicated the strong potential for the project’s membrane-based capture technology to meet and exceed the U.S. DOE NETL Carbon Sequestration Program goals in step-change fashion.

However, these analyses also made clear the need to minimize the membrane support costs, maximize membrane flux, and increase the area density realized by the ultimate module design. To that end, the primary focus is the continued development and demonstration of polymer-based membrane chemistries, structures, deployment platforms, sealing technologies, and separation schemes that achieve the critical combination of high selectivity, high permeability, chemical stability, and mechanical stability, all at elevated temperatures (>150°C), and are packaged in a scalable, economically viable, high-area-density system amenable to incorporation into an advanced integrated gasification combined-cycle (IGCC) plant for precombustion CO_2 capture. Stability requirements are focused on tolerance to the primary synthesis gas components and impurities at various locations in the IGCC process. Since the process stream compositions and conditions (i.e., temperature and pressure) vary throughout the IGCC process, the project is focused on the optimization of a technology that could be positioned upstream or downstream of one or more of the water-gas-shift reactors (WGSRs) or that could be integrated into a WGSR.

Relationship to Program:

This project will support important membrane advances within the CO_2 capture pathway of the NETL Carbon Sequestration Program. The ultimate achievement in the area of CO_2 capture is the production of a CO_2-rich stream at pressure using methods compatible with the overall program research goals of achieving 90% CO_2 capture with less than a 10% increase in the cost of energy services. This project is aligned directly with these capture goals and utilizes a precombustion capture approach focused on the integration of high-temperature polymer-based membranes into an advanced IGCC process.

Validated via membrane productivity (separation factor and flux) comparisons, the materials and membranes that have been developed and that continue to be optimized as part of this project outperform any polymer-based membrane that is commercially available or reported in the literature for separations involving hydrogen, The improved performance of this technology in an application such as IGCC-integrated capture is further substantiated by the accessible operating temperature range (up to 400°C), long-term hydrothermal stability, sulfur tolerance, and overall durability of the composite membrane materials in these challenging precombustion environments. Additionally, the modular, low-maintenance, and flexible design of membrane technology combined with the technology achievements anticipated over the course of the life of this project make this process an exceptional candidate for use for precombustion capture of CO_2. The achievement of the objectives set forth in this project will result in a non-incremental improvement in the combined economics and performance achievable by a precombustion capture technology, and the corresponding development and demonstration of a new separations tool that meets and exceeds, in step-change fashion, the DOE goals for carbon capture.

Primary Project Goal:

The goal of this work is to develop and demonstrate a polymer membrane-based separation technology for precombustion hydrogen purification/carbon capture that can operate under the broad range of conditions relevant to the power industry. This goal also aims to achieve this while meeting the DOE Carbon Sequestration Program goals of achieving 90% CO_2 capture with less than a 10% increase in the cost of energy services.

Objectives:

Previous work by the LANL team has demonstrated that PBI-based chemistries show promise as membrane materials for precombustion capture of CO_2. The primary objectives of this project include the following:

- To continue to develop and demonstrate PBI-based materials and morphologies as a separation media for hydrogen purification and carbon capture
- To demonstrate the performance of those materials in industrially relevant process streams
- To further develop fabrication methodologies and separation schemes to support the technically and economically viable integration of a

precombustion CO_2 capture system that is based on these materials into an advanced IGCC plant

There are numerous steps involved in realizing these objectives. The work to be conducted by the project team is aimed at addressing a critical subset of those steps with a focus on materials design and demonstration. The subset addressed includes the following tasks:

1. Developing and demonstrating high-temperature PBI-based membrane chemistries and morphologies for carbon capture and hydrogen purification from a coal-derived shifted syngas IGCC process stream.
2. Developing the capability to deposit/fabricate thin membrane selective layers on microporous substrates with the goal of fabricating a hollow-fiber membrane with a membrane selective layer that is composed of the PBI-based polymers of interest. As defects on the angstrom size scale will render membranes useless for this difficult gas separation, fabrication/deposition of this defect-free layer via a commercially viable method is critical to commercial realization of this technology.
3. Developing the materials and techniques required to successfully mount the produced fibers into a cartridge/module is essential. For fiber production to be of value, a barrier/potting material and sealing technique compatible with the target process' thermal, chemical, and mechanical environments must also be achieved.
4. All of the aforementioned developments must be utilized together to ultimately achieve a module package that can be tested for permselectivity character in simulated and, ultimately, real process environments. This task includes validation of materials and methods developed both by LANL and other DOE NETL project teams as requested by NETL project management.

03: ORD-GEC.1610251.600.B

Project Number ORD- GEC.161025 1.600.B	**Project Title** Geologic Sequestration - Wellbore/Seal Integrity Project			
Contacts DOE/NETL Project Mgr.	**Name** Brian Strazisar	**Organization** NETL – Office of Research and Development	**Email** Brian.Strazisar @netl.doe.gov	
Principal Investigator	Brian Strazisar	NETL – Office of Research and Development	Brian.Strazisar @netl.doe.gov	
Partners	Indiana Geological Survey National Risk Assessment Program University of North Dakota-EERC University of Oregon University of Texas at Austin			
Stage of Development				
__ Fundamental	_X_ Applied R&D	___ Proof of Concept	__ Prototype Testing	__ Demonstration

Technical Background:

The effectiveness of carbon dioxide (CO_2) sequestration in geologic reservoirs depends greatly on storage permanence; for this reason, a key goal of the NETL Carbon Sequestration Research Program is 99% retention of CO_2 in a reservoir over a 100-year time period. Currently, there is insufficient scientific basis to reliably predict the probability or rate of leakage because variability in field conditions complicates quantitative predictions of leakage risk. Of the many variables being considered, wellbore systems are one of the most obvious potential leakage pathways for buoyant CO_2 injected into geologic formations for storage. Wellbore integrity is therefore the main focus of this project, with some focus on natural fractures or faults in sealing units (i.e., caprocks), which could potentially lead to leakage.

The majority of locations under consideration for CO_2 injection and sequestration are found in areas that have a history of oil, natural gas, and/or coal bed methane production. These areas are being considered due to value-added opportunities such as enhanced oil recovery, enhanced gas recovery, and enhanced coal bed methane recovery. There also exists a greater knowledge base for saline formations that lie either above or below oil and gas reservoirs due to well logging and exploration activities. As a result of human activity, these formations are typically punctured by a significant number of wells from both exploration and production. No matter how impermeable an overlying caprock is, the sealing integrity may be compromised by the presence of wells. Therefore, wellbores represent the most likely route for CO_2 leakage from geologic carbon sequestration.

Abandoned wells are typically sealed with cement plugs intended to block vertical migration of fluids. In addition, active wells are usually lined with steel casing, with cement filling the outer annulus in order to provide structural support and prevent leakage between the casing and the formation rock. The permeability and integrity of the cement will determine how effective it is in preventing leakage.

The evaluation of the risks involved with CO_2 sequestration requires an estimate of the leakage rate of CO_2. This requirement is embodied in the wellbore leakage model developed at Princeton University, which attempts to evaluate overall leak rate at the field scale, given a particular well distribution and with individual well permeabilities. This model has been incorporated into the CO_2 Prediction of Engineered Natural Systems risk assessment model; however, there is insufficient knowledge at present to determine the effective permeabilities that are used as inputs in the Princeton model. In the hypothetical cases that the Princeton researchers investigated, they randomly assigned "leaky" well permeabilities from an arbitrary frequency distribution of permeabilities. Their models were not based on measurements of actual wellbore leaks and do not include features such as geochemistry, geomechanics, or wellbore construction that are likely to have a significant impact on the temporal evolution of leakage frequency.

The purpose of this project is to reduce uncertainties in risk assessment by providing leakage frequency and rate estimates based on a better understanding of the processes that affect reservoir integrity. This project will be carried forth as a key part of the National Risk Assessment Program, a collaborative effort among five national laboratories (NETL, Los Alamos National Laboratory, Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, and Pacific Northwest National Laboratory) to address all of the key scientific issues needed to quantitatively assess risk for geologic carbon sequestration.

Relationship to Program:

This project will support advances in wellbore and seal integrity understanding within the CO_2 storage pathway of the NETL Carbon Sequestration Program. Currently, estimating leakage probability and rate is difficult due to the scarcity of field data and the great variability in conditions. By individually studying key processes over a relevant range of conditions, uncertainty can be significantly reduced and reasonable estimates of leakage risk can be provided.

Primary Project Goal:

The focus of this project is to develop the scientific foundation necessary to ensure the performance of seals, including wellbores, with respect to the long-term storage of CO_2.

Objectives:

Project work this year will focus on the synthesis of an extensive set of efforts focused on wellbore integrity, with the intent of producing summary assessments of key controlling phenomena, documenting best practices, and reassessing key gaps in knowledge. The specific tasks within this project will address the following eight key objectives. Each task addresses a specific parameter or variable that has an impact on seal integrity. Each task also lists a deliverable and a fiscal year 2010 (FY2010) milestone.

TASK 1: ASSESS IMPACT OF BRINE CHEMISTRY ON REACTION RATE AND MECHANISM FOR ALTERATION OF TYPICAL WELL CEMENTS.

Previous experiments have determined the detailed reaction mechanism and rate for cement alteration due to CO_2 exposure in the presence of simple sodium chloride brine. Due to the complexity of cement systems in a natural environment, it is likely that the brine composition will have a significant impact on the chemical reactions. This task focuses on the most important components of typical natural brines so that the chemistry of cement alteration can be predicted over a broader range of conditions.

FY2010 Milestone. Complete initial experiment on influences of brine chemistry on cement/brine/CO_2 interactions.

Deliverable. Manuscript on brine influences on CO_2/cement interactions

TASK 2: ASSESS IMPACTS OF CONSTITUENTS (E.G., HYDROGEN SULFIDE [H_2 S], OXYGEN [O_2], SULFUR DIOXIDE [SO_2]) ON REACTION RATE AND MECHANISM FOR CEMENT INTERACTIONS.

To this point, most work on carbon sequestration has assumed the injection of “pure” CO_2. However, there would be a significant economic advantage (on the capture side) to storing CO_2 along with one or more co-contaminants such as H_2,S, O_2, or SO_2. This task is aimed at determining the impact that such gases would have on wellbore cement integrity.

FY2010 Milestone. Submit manuscript on impact of H_2 S on cement/brine/CO_2 interactions.

Deliverable. Series of manuscript on impact of contaminants on cement/brine/CO_2 interactions

TASK 3: ASSESS CHEMICAL REACTIONS THAT COULD BE IMPORTANT TO FRACTURES THROUGH TYPICAL SEALS AND WELLBORES, AND INITIATE EXPERIMENTS TO DETERMINE OPEN/CLOSE CONDITIONS.

Much of the previous work on cement alteration has taken place in static systems. Wellbores that have initial flow paths due to poor completion or inadequate bonding to the rock or steel casing are much more likely to lead to leakage. There can also be active flow paths along faults or fracture networks in the caprock. Chemical reactions could result in dissolution of material along a flow path, which could lead to enhanced flow or could result in the precipitation of material, which could lead to reduced flow or even the sealing of a pathway. This task consists of flow-through experiments to determine which conditions will cause a path to open or close.

FY2010 Milestone. Complete initial experiments on flow of carbonated water through cement channels over an appropriate range of channel sizes and flow velocities.

Deliverable. Manuscript on open/close conditions for caprock and wellbore fractures

TASK 4: ASSESS IMPACT OF CHEMISTRY AT WELLBORE INTERFACES ON SEAL INTEGRITY.

Chemical reactions from CO_2/brine exposure are most difficult to predict along the interfaces between reactive solids due to the number of competing processes. These locations include mainly the cement-rock interface and the cement-steel interface. This task uses static experiments to characterize the nature and rate of chemical reactions that occur at the interface, with the objective of determining their impact on wellbore integrity and potential leakage.

FY2010 Milestone. Complete conceptual model for chemical reactions at an interface.

Deliverable. Manuscript on chemical interactions at rock-cement and cement-steel interfaces

TASK 5: ASSESS DIFFUSION-LIMITED SCENARIO FOR CORROSION UP A WELLBORE.

Early results in this project have shown that wells are unlikely to leak due to cement alteration under normal conditions in the absence of an initial flow pathway. This unlikely leakage is due to the fact that alteration is diffusion-limited, and diffusion through cement (a material with very low permeability) is slow. This

task will use experiments and analytical modeling to predict the possible impact of diffusion-limited alteration over a wide range of conditions. The results will define a worst-case scenario by determining how poor quality (i.e., high permeability) cement must be initially for diffusion-limited alteration to lead to a leakage risk.
FY2010 Milestone. Complete initial experiments to estimate penetration time for 100 feet of cement plug based on initial permeability.
Deliverable. Manuscript that reports estimate of penetration depth for diffusion-limited reaction of CO_2/water/cement

TASK 6: ASSESS GEOMECHANICAL CHANGES ON SEAL INTEGRITY.

Although the main focus of this project is on chemical interactions and flow properties, mechanical properties of wellbore material will also play a significant role in determining leakage risks. This task is focused on determining the impact of CO_2 exposure on the geomechanical integrity of wellbore materials.
FY2010 Milestone. Initiate experiments to determine strength changes in seal material due to CO_2 exposure.
Deliverable. Manuscript on strength changes in seal materials due to CO_2 exposure

TASK 7: ASSESS THE IMPACT OF BIOLOGICALLY-MEDIATED DISSOLUTION AND PRECIPITATION OF MINERALS ON SEAL INTEGRITY.

The goal of this task is to develop a fundamental understanding of biomineralization along interfaces such as wellbores and fractures in geologic reservoirs, including the mechanisms and magnitudes of microbial processes occurring during geologic sequestration of $CO_{2.}$ These insights will suggest the means by which microbial processes may be optimized for enhanced carbonate precipitation, maximized subsurface capacity, and minimized leakage during CO_2 sequestration.
FY2010 Milestone: Obtain fluid sample from a Phase III site, and complete experiment to identify deep subsurface microbial populations.
Deliverable: Manuscript on subsurface microbial populations at Phase III site and their impact on seal integrity

TASK 8: ASSESS POTENTIAL OF COAL SEAMS AS SECONDARY SEALS.

Due to the low permeability of many coal seams, it has been proposed that they may act as a secondary seal in some carbon sequestration reservoirs, potentially leading to decreased leakage risk. This task will assess the feasibility of using coal seams as secondary seals. Field data surveys will determine potential candidate seams, while simulation and laboratory experimentation will determine flow properties such as permeability and CO_2 sorption capacity.
FY2010 Milestone. Complete initial tests to determine the feasibility of the concept of coal seams as secondary seals for major geologic formations relevant to CCS.
Deliverable. Manuscript on feasibility of coal seams as secondary seals

04: FWP-45502/FWP-58159

Project Number	Project Title			
FWP-45502/ FWP-58159	Sequestration of CO_2 in Basalt Formations			
Contacts	**Name**	**Organization**	**Email**	
DOE/NETL Project Mgr.	Dawn Deel	NETL – Carbon Sequestration Division	Dawn.Deel@ netl.doe.gov	
Principal Investigator	B. Peter McGrail	Pacific Northwest National Laboratory	Pete.McGrail@pnl.gov	
Partners				
Stage of Development				
_X_ Fundamental R&D	__ Applied R&D	__Proof of Concept	__ Prototype Testing	__Demonstration

Technical Background:

Numerous site assessments for geologic sequestration of carbon dioxide (CO_2) have been conducted in virtually every region of the United States. However, basalt formations have received limited attention with respect to their potential for permanent sequestration of anthropogenic CO_2. Major basalt formations occur in all parts of the world that may be attractive for carbon dioxide sequestration, including the United States and India. Unlike sedimentary rock formations, basalt formations have unique properties that will chemically trap the injected CO_2, effectively isolating it from the atmosphere permanently.

The dissolution kinetics of various volcanic province basalts have been measured as a function of temperature and pH. The results of these experiments demonstrate the response of different basalts to mildly acidic pore waters, similar to conditions expected in a CO_2 sequestration scenario. Measuring the dissolution kinetics establishes essential data needed to model the rate at which CO_2 reacts with basalt and the speed at which carbonate minerals can form in situ. Fully coupled reactive transport simulations of a 600-kiloton-per-year injection into Columbia River basalts were performed. These simulations indicated that over 80% of the injected CO_2 would be mineralized in less than 100 years. However, these calculations neglected mineralization reactions occurring in the supercritical CO_2 ($scCO_2$) phase itself, a discovery made on this project that has significant implications for virtually all sequestration projects. Similar calculations for small-scale research pilots indicate that validation of in situ mineralization is possible by monitoring pore fluid chemistry and potentially core samples retrieved 2 to 3 years post-injection. Long-term $scCO_2$ experiments (up to 4 years' duration) with various basalts have also been performed and provided the first conclusive laboratory evidence of the rapid mineralization potential of basalt formations. Despite very similar bulk chemical composition and mineralogy, significant differences in the mineralization rates among basalts have been measured, with Newark Basin basalts being the most reactive.

The first comprehensive map of deep flood basalts (those suitable for sequestration) was developed, and the information was provided to NatCarb. Major flood basalts in the Pacific Northwest and southeastern United States lack significant storage capacity in more conventional rock types. A literature database of hydrogeologic properties of basalt aquifer systems was also assembled in order to bound injection rates into flood basalts.

Relationship to Program:

This project will support important basalt site assessment advances within the storage pathway of the NETL Carbon Sequestration Program. Because of concern over the impact of increasing emissions of greenhouse gases on global climate change, considerable effort is being expended to evaluate the potential of CO_2 sequestration to mitigate the buildup of CO_2 in the atmosphere. The success of this project will expand the viable geologic options for CO_2 sequestration in the continental United States and provide heretofore unexplored options for CO_2 sequestration in developing countries, such as India, that are now known to have limited sedimentary basin storage capacity. Basalt formations have a unique chemical makeup that could potentially convert all of the injected CO_2 to a solid mineral form, thus isolating it from the atmosphere permanently.

Laboratory experiments conducted under this program led one of the seven regional partnerships (Big Sky Carbon Sequestration Partnership) to select basalt formations in eastern Washington State as a pilot testing site to evaluate the potential long-term CO_2 storage option. As the primary focus of Phase II, a small-scale pilot test will inject 1,000 tons of CO_2 into deep basalt formations to determine the capacity, injectivity, and mineralization rates in deep mafic rock formations. These decisions were based on long -term experimental results from this project, in which it was determined that CO_2 reacts with basalt formations to produce stable carbonate minerals in a relatively short time period (<1 year). Work on this project can also be cited as supporting the selection of the first commercial-scale feasibility study for CO_2 storage in basalts. This feasibility study will determine whether approximately 700 kilotons per year of CO_2 captured from a pulp and paper mill can be injected and permanently stored in the Colorado River Basin. This study was one of 12 industrial carbon capture and storage projects selected by DOE in October 2009. Pacific Northwest National Laboratory is also partnering with the University of Hawaii to study $scCO_2$ and mixed gas interactions with Hawaiian basalts retrieved from a recent deep drilling project conducted on the main island of Hawaii.

The international impacts of this project include the expansion of India's sequestration program to include basalt formations as a viable storage option. India's Deccan Traps are one of the largest continental flood basalt formations in the world. Deccan samples tested under this program show that reaction with CO_2 results in the formation of carbonate minerals. Additional, published journal articles and presentations at international conferences are currently influencing injection strategies at the CarbFix project in southwestern Iceland, which is conducting a field-scale CO_2 injection into basalts. The source of the CO_2 for the CarbFix project contains approximately 16% hydrogen sulfide (H_2S). Research from this project on multicomponent gas systems has shown that the presence of even small quantities of H_2S (<1%) in CO_2 can severely impact carbonation in some basalts through the formation of pyrite coatings.

Primary Project Goal:

The purpose of this project is to conduct research needed to address commercial-scale injection strategies, CO_2 fate and transport, and improved seismic imaging methods for basalt characterization to provide a path forward for eventual commercial use of basalt formations for CO_2 sequestration.

Objectives:

The objective of this project is to evaluate formation suitability for CO_2 storage and the rate of conversion of injected CO_2 to carbonates, with a principal focus on basalt formations in the United States and India. By exposing various basalt samples to conditions relevant to sequestration of CO_2 and mixed gas systems, reaction kinetics, relative carbonate mineralization rates, and overall suitability of individual basalt formations will be assessed.

05: FWP-FE-10-001 Task 3

Project Number FWP-FE-10-001 Task 3	**Project Title** Systems Modeling & Science for Geologic CO_2 Sequestration			
Contacts DOE/NETL Project Mgr.	**Name** Darin Damiani	**Organization** NETL – Carbon Sequestration Division	**Email** Darin.Damiani@netl.doe.gov	
Principal Investigator	Rajesh Pawar	Los Alamos National Laboratory	rajesh@lanl.gov	
Partners	Colorado School of Mines			
Stage of Development				
X Fundamental R&D	__ Applied R&D	__ Proof of Concept	__Prototype Testing	__Demonstration

Technical Background:

Carbon dioxide (CO_2) capture coupled with geologic storage (CCS) is one of the technologies currently being investigated for mitigating increasing atmospheric CO_2 concentrations. An integrated CCS technology has multiple components, including CO_2 sources (e.g., fossil fuel-based power sources, refineries, cement plants, and fertilizer plants), transportation infrastructure, and CO_2 storage reservoirs. If CCS is to play a critical role in the future of fossil fuel utilization, its effectiveness against multiple criteria needs to be understood. Assessing the effectiveness of CCS will require understanding the complex interplay between the various coupled subsystems and predicting how the integrated system will behave. For example, the amount of CO_2 that needs to be sequestered from a power plant will depend on the type of power plant, its operating conditions, coal composition, and capture technology. The amount of CO_2 that can be transported from a power plant and sequestered will depend on the type and availability of transportation infrastructure as well as the availability of suitable geologic sites that can effectively store CO_2 over a long time period. The infrastructure to handle and inject CO_2 at a storage site will be a function of the CO_2 output from the power plant, while the rate and conditions at which CO_2 is delivered from the power plant to the storage site will depend on available storage capacity as well as changes in the in situ pressure in the storage reservoir. As the sequestration capacity of a storage reservoir changes, it will affect decisions related to power plant operations and the need for additional storage sites.

Developing a capability to model such a complex system is challenging because it has multiple, coupled components that are governed by different physics. It is significantly difficult to develop a single numerical model for simulating an integrated CCS system with all of the necessary physics. On the other hand, it is possible to develop system-level models that integrate various subsystems that are governed by different physics. Over decades, DOE has evolved an approach encompassed by the concept of science-based prediction that links high-level systems models to detailed models of physical and chemical processes by integrating theory, observation, experiment, and simulation. These system-level models can be used for decisionmaking, and the approach has been applied, among other things, to evaluating long-term performance of engineered geologic systems. The approach enables performance-based decisions related to such systems, given wide ranges in scale (both length and time), process interdependencies, uncertainties, and geologic heterogeneities. For engineered geologic sites, the linkages are made through abstractions, simplified models, analytical models, or detailed process-level models (as appropriate) that are developed explicitly or implicitly on detailed physics and chemistry. In order to develop these models, it is necessary to understand and characterize the underlying physical and chemical processes through application of theory, numerical simulations, laboratory experiments or field observations from analog sites, and demonstration projects. Thus, the science-based prediction approach facilitates the integration of a wide range of research and development activities that are focused on developing the underlying science.

Currently, there is no single system model available that can be applied to an integrated CCS application, but a few efforts are under way that have been developing modeling capabilities that, when combined appropriately, can be used to model an integrated CCS operation. NETL has developed the Advanced Process Engineering Co-Simulator (APECS) model, which can be used to integrate various subsystems in a coal-fired power plant and simulate its overall performance. The project team at Los Alamos National Laboratory (LANL) has been developing the CO_2 Prediction of Engineered Natural Systems (CO_2-PENS) system-level framework and a model (based on the framework) that can be used to simulate an integrated CCS system. The current CO_2-PENS version has models to account for power plant, pipeline, and geologic storage reservoir subsystems. However, the current models for power plant and transport pipelines are extremely simple and not as advanced as the model for geologic storage reservoir subsystems. The LANL team has also been developing an optimization approach, spatial infrastructure model for CCS (SimCCS), which can be used to simulate development of a pipeline network, while taking into account a number of factors affecting the pipeline infrastructure. The project team's goal is to develop an approach that is primarily focused around CO_2-PENS but that integrates it with the APECS and SimCCS models.

CO_2-PENS is the first system model developed for assessing the overall performance of a CCS operation. It integrates modules that describe the entire CO_2 capture and sequestration pathway, starting from capture at a power plant and continuing through transportation pipelines to the storage reservoir. At the storage reservoirs the simulation of CO_2 migration continues through the subsurface as it interacts with the sequestration reservoir and potential leakage pathways such as wellbores, faults, and overlying caprock. Potential migration of CO_2 outside the primary sequestration reservoir is followed along the pathways into shallow formations, including other resources, and ultimately to the atmosphere. As mentioned earlier, a significant amount of the CO_2-PENS developmental effort has focused on developing modules within the geologic storage subsystem. These include modules to simulate CO_2 injection, migration in the reservoir, potential migration along the leakage pathways, potential migration in shallow formations, and potential release to the atmosphere. The processes within these modules are simulated through analytical models, abstractions, or linkages to process-level simulators. CO_2-PENS is developed using the GoldSim platform, which has been used extensively to develop models for a wide range of risk-assessment applications. A powerful underlying stochastic framework at the system level allows CO_2-PENS to be used to explore complex interactions among a large number of uncertain variables. CO_2-PENS provides results that can be used to assess deployment of an integrated CCS system using various criteria including costs, infrastructure requirements, and potential risks due to leakage.

CO_2-PENS development has been funded entirely by DOE. The LANL team initially developed the overall concept, the underlying framework, and an initial version of the CO_2-PENS system model through the Zero Emission Research & Technology (ZERT) project. They then focused their efforts on applying the CO_2-PENS framework to two field sites: the West Pearl Queen CO_2 sequestration field demonstration project and the Scurry Area Canyon Reef Operators Committee (SACROC) Enhanced Oil Recovery (EOR) project. In addition, LANL further developed the CO_2-PENS system model to increase its complexity. The goal of this effort was to develop capabilities that would allow the system model to be applied to specific sites and to be able to incorporate site-specific details. This work was supported by DOE through the Geologic Risk Assessment project. As part of this effort, the project team has been working on releasing an executable form of the CO_2-PENS model to the larger sequestration community for use and comments in early 2010. In fiscal year 2009 (FY2009), the team has initiated activities to advance capabilities for the parts of CCS operations other than the geologic reservoir. These include CO_2 sources, pipelines, injection facilities, and potential facilities for brine production and treatment. During this project LANL will build upon these advances with an overall project goal of having a systems-modeling capability that can simulate an integrated CCS operation from source to sink (and beyond).

Relationship to Program:

This project will support important systems-modeling advances within the simulation and risk assessment pathway of the NETL Carbon Sequestration Program. At the successful conclusion of this project, the project team expects to develop a systems-modeling capability that can be used to assess the overall effectiveness of CCS technology. The capability will be of significant use to a wide range of decision-making users, including power plant operators, pipeline developers, sequestration site operators, and regulators. The project team also intends to make the capability developed during this project available to the larger CCS community, similar to the release of the current version of CO_2-PENS, which is focused on long-term performance assessment of geologic storage reservoirs.

Primary Project Goal:

The primary goal of this project is to develop a capability that can be used to assess effectively the overall performance of an integrated CCS operation using multiple criteria.

Objectives:

Activities in this project are focused on developing a first-ever integrated systems-modeling capability that can be used to simulate performance of an entire CCS operation. The capability will be primarily based on LANL's CO_2-PENS model. To date, the CO_2-PENS development effort has focused on simulating CO_2 injection, migration, and subsequent interactions in geologic reservoirs and on assessing long-term performance of geologic CO_2 storage reservoirs. This project will lead to enhancements that advance the current capabilities for modeling CO_2 sources and the CO_2 transportation network. The project team will develop and advance system models for brine production and treatment. In addition to the system-model development, the project will also advance the science of multiphase CO_2 flow in shallow aquifers, which is a critical need for geologic CO_2 sequestration. Further discussions of these tasks are below.

MODULE FOR CO_2 SOURCE

An integrated assessment of a CCS project will have to take into account the interdependence of CO_2 sources and storage reservoirs. The current CO_2-PENS model has simple abstractions for simulating CO_2 sources. Unlike the system model for the geologic reservoir in which subsystems such as storage reservoirs, wells, faults, and shallow aquifers are explicitly defined and integrated, the system model for power plants does not include a similar level of granularity. A realistic integrated assessment will need to take such granularity into account since the overall CCS system performance will depend on it. In order to bring in the necessary granularity for the power plant the project team has proposed linking the CO_2-PENS model to the APECS model developed by NETL. They will be building on the effort initiated as part of their systems-modeling project funded during FY2009. APECS has been used to simulate performance of a power plant by integrating models for various subsystems in the plant. It provides the necessary granularity to characterize the impact of variability in operating conditions, power plant configurations, coal compositions, and other factors on CO_2 output. The project team's overall objective for this activity is to develop an integrated modeling capability that includes both the APECS and CO_2-PENS model. With this capability the user should be able to simulate a power plant coupled with a geologic sequestration reservoir. This effort will require significant developments since the two models use different modeling approaches. LANL's initial efforts will be focused on defining the requirements for establishing linkages between the two models. Initially this development will be as simple as providing the amount of CO_2 output from a power plant simulated by APECS to the CO_2-PENS model and replacing the current model that calculates the CO_2 output from a power plant. APECS models the power plant by taking into user-defined plant specifics into account. This capability represents a significant advancement over the current CO_2 source model. This will be a one-way link without any iterative aspect.

The challenging part of development will be to establish dynamic linkages between the two models. These linkages will provide the ability to account for changes in the power plant configurations and the geologic reservoir conditions, as well as to determine how each model affects the performance of the other. This effort will require establishing mechanisms to provide feedbacks between the two models. Potential feedbacks include loss of a sink's capability to store CO_2 or the utilization of brine produced during CO_2 sequestration operation for power plant cooling. The latter will benefit from a subsystem module for brine treatment that the LANL is planning to develop as part of this project (as discussed later). The project team will interact closely with the NETL experts developing the APECS model to define the requirements for dynamic interactions and subsequent developments for computationally efficient interaction between the two models. Note that the ultimate project objective is not to develop an entirely new simulation capability but to develop an approach that will allow effective and efficient integration of the two models. Once the team has developed an integrated modeling capability, they will test it by applying it to a diverse set of integrated CCS systems with different types of sources (e.g., varying coal types and capture technologies) and geologic storage reservoirs. The types of problems and the scope of demonstration will depend on the extent of the linkages between the two models.

MODULE FOR CO_2 TRANSPORT

Similar to the subsystem model for CO_2 source, the current model for CO_2 transport in CO_2-PENS is extremely simple. The project team's overall objective for this activity is to develop a capability that can be used to simulate the integrated

CCS operation that includes the CO_2 pipeline infrastructure. Similar to the earlier activity focused on developing the CO_2 source module, this activity will also be building upon the efforts initiated during FY2009. LANL's overall approach is to couple the CO_2-PENS model with another LANL modeling capability, SimCCS, which was initially developed as part of the ZERT project. SimCCS can be used to determine where to build an efficient pipeline network in order to minimize the transportation costs. The pipeline construction costs take into account factors including topography, population centers, right of way, roadways and rails, and national parks. Similar to APECS, SimCCS uses a different modeling approach than CO_2-PENS. SimCCS is essentially time independent, and its output for CCS infrastructure is designed for a single time step. The project team will use a two-step approach to integrate the two models. In the first step they will integrate the models through a one-way coupling. First, SimCCS will take input from CO_2-PENS on reservoir storage capacity (including distributions) and generate pipeline infrastructure. This task will use the current cost surface model in SimCCS, which is qualitatively derived and has a spatial resolution that is too high to adequately model an integrated CCS system at the regional scale. Next, the project team will enhance the current cost surface model to a quantitatively derived and empirically calibrated cost surface that can be reproduced to account for regional differences and automatically adjust for spatial resolution. The team will repeat the calculations performed in the first step with the new cost surface. The one-way coupling will be further enhanced to account for costs associated with operating geologic sites and risks associated with sinks. The one-way integration will provide LANL with insights into what will be necessary to develop dynamic linkages between SimCCS and CO_2-PENS. Linkage development may include introducing time steps into the SimCCS model without pushing the model toward intractability and establishing dynamic feedback between the two models, which will be difficult as SimCCS is an optimization model while CO_2-PENS is not. Once an efficient approach is determined, the two models will be integrated with dynamic feedback. Ultimately, the integrated modeling capability will be tested and demonstrated through its application to appropriate problems.

MODULE FOR BRINE PRODUCTION AND DISPOSAL

Large-scale injection of CO_2 during geologic sequestration operations will lead to large-scale displacement of brine. Changes in in situ reservoir pressures and brine movement are identified as major risk concerns for geologic sequestration. One potential risk mitigation option is to utilize a reservoir-management approach by producing brine to maintain reservoir pressure and minimize lateral brine movement. Similar approaches are used in CO_2 EOR operations. While brine production may mitigate subsurface risks, it is necessary to identify what can be done with produced brines. Options that can be explored include reinjection or treatment for beneficial reuse that could potentially include utilization in power plant operations. In order to assess the effectiveness of this approach, it is necessary to perform system-level calculations that integrate CO_2 injection, brine migration, and above-surface facilities necessary for brine treatment and either disposal or reuse. The overall objective of this activity is to develop capabilities in CO_2-PENS that can be used for assessing the brine production and disposal issues. The module for brine production and treatment will include components for brine production, including production wells, collection facilities, treatment facilities, and disposal facilities. Development of a module requires identification of these components, their interrelationships, and the development of abstractions/models for individual components. Models for individual components will take into account volume, energy, and chemical balances. The project team will also account for costs and regulatory constraints related to disposal of treated brine. LANL will use data from currently operating desalination and brine-treatment plants. The ultimate project objective is to develop a comprehensive module that provides a capability to take into account various complexities associated with brine production and treatment. The module will take input from the injection module in CO_2-PENS on the amount of brine that could be produced during sequestration operations. The module will be part of the integration between CO_2-PENS and APECS as well. During this activity the project team will also collaborate extensively with other DOE-funded projects that are focused on large-scale brine movement and treatment. Ultimately, the modeling capability and its utility for assessing effectiveness of brine production, treatment, and disposal will be demonstrated through its application to an appropriate problem.

CHARACTERIZATION OF CO_2 FLOW IN SHALLOW SUBSURFACE

Migration of CO_2 to shallow aquifers as well as the shallow subsurface is identified as one of the risk concerns of geologic storage. Conceptual models for CO_2 flow in shallow subsurface have been proposed, but these models have not been validated through laboratory and/or field experiments. Field experiments on the release of CO_2 in shallow subsurface have been pursued as part of the ZERT project, but the focus of the experiments is primarily on testing the effectiveness of monitoring technologies. The resulting data are limited for their applicability to the characterization of CO_2 flow in shallow aquifers. The overall objective of this activity is to characterize the mechanisms through which CO_2 flows in shallow aquifers and develop predictive modeling capabilities that can be used in numerical simulators as well as system models. In this activity, LANL will utilize an integrated approach, which combines laboratory experiments and numerical simulations, with the goal of understanding and characterizing CO_2 flow in shallow subsurface.

The LANL team will collaborate with Dr. Tissa Illangasekare of the Colorado School of Mines. Dr. Illangasekare is extremely well recognized for his contributions to experimental hydrology. His experimental facilities are uniquely suited for carrying out laboratory experiments associated with this activity. Dr. Illangasekare's laboratory is equipped with tanks that can be filled with well-characterized sands to create models for shallow subsurface. This facility has been used to perform experiments focused on characterizing multiphase fluid flow in heterogeneous aquifers. As part of this project, the project team will utilize Dr. Illangasekare's expertise and experimental facilities to characterize CO_2 flow in shallow subsurface. The experimental effort will be multipronged. First, LANL will utilize column experiments to characterize and model multiphase flow mechanisms in shallow subsurface, including bubble flow (as may be the case during slow CO_2 release). These experiments will be performed using uniformly packed sand columns and various configurations of CO_2 release and flow. Following the column experiments, the project team will perform flow experiments in two-dimensional tanks. Multiple boundary conditions and sand packing representing various aquifer configurations will be utilized. The two-dimensional multiphase flow will be characterized through observations on pressure, temperature, saturation, pH, and other conditions. The effects of heterogeneity, water saturations, and modes of CO_2 release will be studied through various experiments. Ultimately, the experimental data and observations will be used to develop and validate conceptual models for CO_2 flow in shallow subsurface in Finite Element Heat and Mass Transfer Code (FEHM), LANL's porous media fluid-flow simulator. Results of this work will be timely and will provide input to the National Risk Assessment Program.

06: FWP-ESD09-056 Task 5

Project Number FWP-ESD09-056 Task 5	**Project Title** Regional Modeling of Large-Scale Hydrologic Impact of CO_2 Storage			
Contacts DOE/NETL Project Mgr.	**Name** Karen Cohen	**Organization** NETL – Carbon Sequestration Division	**Email** karen.cohen@ netl.doe.gov	
Principal Investigator	Jens Birkholzer	Lawrence Berkeley National Laboratory	JTBirkholzer@lbl.gov	
Partners				
Stage of Development				
_X_ Fundamental R&D	__Applied R&D	__Proof of Concept	__Prototype Testing	__ Demonstration

Technical Background:

MOTIVATION

If carbon dioxide (CO_2) capture and storage (CCS) technologies are implemented on a large scale, the amount of CO_2 injected and sequestered underground will be extremely large. Various research studies have been conducted to date evaluating the hydrogeological conditions under which the injected volumes of CO_2 can be safely stored for hundreds or even thousands of years. For example, many of these studies address issues such as the long-term efficiency of structural trapping of CO_2 under sealing layers, or the importance of other trapping mechanisms, including dissolution of CO_2 into formation water or mineral trapping as CO_2 reacts with the rock. Less emphasis has been placed on the issue of regional-scale pressure buildup and brine migration in saline reservoirs from the displacement of the native brines or brackish waters by the injected volumes of CO_2. Large-scale injection of CO_2 may impact subsurface volumes that can be significantly larger than the CO_2 plume itself. Thus, even if the injected CO_2 is safely trapped in suitable geological structures, large-scale injection and related brine displacement may affect shallow groundwater resources. This issue of pressure buildup and brine displacement, and its possible environmental impact on groundwater resources, is being addressed in this research effort.

BUDGET PERIODS

The project has been organized in two budget periods. The first three-year budget period started with fiscal year 2007 (FY2007) and is about to be finalized. This budget period is followed by another three-year continuation period from FY2010 through FY2012.

As discussed in more detail below, the project research conducted to date evaluated the potential magnitude of large-scale brine pressurization and migration resulting from the storage of large volumes of CO_2. Predictive simulations were conducted to assess a range of geological conditions and possible future sequestration scenarios for idealized geologic systems and large hydrologic basins with promising CO_2 sequestration potential. The studies show that the areas impacted by pressure changes can be extremely large and that brine pressurization may impact caprock integrity and groundwater resources far away from the injection centers.

Considering the relevance of the observed basin-scale hydrologic impacts, the project continuation will address three main topics: improving the prediction reliability of basin-scale models (model confidence), quantifying the impact of brine pressurization and migration on groundwater resources (impact assessment), and evaluating pressure management schemes via brine extraction (management and mitigation). These topics will include several tasks and subtasks, as outlined further below.

ACCOMPLISHMENTS TO DATE

The primary goal of the first budget period was to develop a better understanding of the potential magnitude and extent of water-pressure increase and brine displacement in deep saline reservoirs in response to full-scale deployment of future CO_2 storage. Several predictive assessment tools featuring different degrees of complexity were developed and utilized, ranging from semi-analytical estimation methods to complex high-performance prediction models. The project team's quantitative evaluations started with systematic studies of the basic processes and key sensitivities of idealized geologic formations, followed by detailed modeling studies of two real-world groundwater basins in the United States that are candidates for future CO_2 storage. Modeling studies of idealized subsurface formations were conducted for two basic CO_2 storage scenarios that experience very different pressurization behaviors (i.e., closed or compartmentalized systems that are laterally confined [e.g., via sealing faults] versus open systems with open lateral boundaries [e.g., extensive saline reservoirs]).

Closed systems were investigated via detailed numerical simulations of CO_2 migration, pressure buildup, and brine displacement, including various sensitivity analyses for injected volume, formation size, hydraulic properties, compressibility, and seal permeability. The storage capacity in a compartmentalized system with impervious seals was found to be generally much smaller than the storage capacity in open systems because overpressure needs to be avoided in the closed systems. The project results demonstrated for the first time the importance of diffuse brine leakage through the upper and lower seals. With seal permeability varying from 10^{-19} m^2 to 10^{-17} m^2, diffuse brine leakage has a moderate to strong effect on reducing or limiting the pressure buildup in the storage formation, thus allowing for considerably higher storage capacity in the compartmentalized system than in a true closed system. Two analytical formulations were developed as alternatives to detailed numerical models. A quick-assessment method allows estimation of pressure buildup and storage capacity in closed systems, with either impervious caprock or an overlying semi-pervious seal. The calculation approach was based on the fact that the injected CO_2 needs to displace native brine of an equivalent volume, and that this equivalent volume is composed of three volume contributions that can be easily calculated: (1) the additional pore volume within the storage formation provided by pore and brine compressibility in response to pressure buildup, (2) the additional pore volume within the sealing units provided by pore and brine compressibility in response to pressure buildup, and (3) the leakage of the displaced brine through the seals into overlying/underlying formations. A complementary semi-analytical solution was developed using Laplace transform solutions, for the evaluation of pressure buildup, leakage rate through seals, and horizontal flux in a laterally open or bounded radial system.

Open systems are representative of the large sedimentary basins in many parts of the United States. They are expected to be a main target for full-scale deployment because of their capacity for receiving large volumes of CO_2. These basins usually exhibit a sequence of high-permeability aquifers and intervening low-permeability aquitards or seals. The project team conducted detailed numerical simulations of transient pressure buildup and brine displacement in an idealized multilayered aquifer-aquitard system, evaluating flow processes both within the deep reservoir as well as through the aquitards upward toward freshwater aquifers. The team's focus here was to understand the importance of interlayer communication as a function of seal permeability. Simulation results confirmed that in laterally open systems, the region of influence in response to CO_2 injection can be extremely large. However, while the pressure pulse may travel fast and far in saturated subsurface formations, the lateral brine flow velocities within the reservoir were found to be quite small, not much larger than those of natural groundwater flows in deep basins. Consistent with the project's finding for closed formations, the permeability of seals has a significant impact on pressure buildup and brine displacement behavior within the storage formation. Seals that are suitable for long-term trapping of CO_2 allow for considerable brine leakage out of the formation vertically upward and/or downward. As a result, the pressure buildup and brine displacement within the storage formation can be strongly reduced compared to a perfect seal with zero or close-to-zero permeability. Interlayer pressure propagation and brine migration through a sequence of aquitards/aquifers is not very likely to affect shallow aquifers. These conclusions may change if the deep and shallow units would communicate via local high-permeability conduits such as faults and abandoned boreholes.

For idealized geologic formations, the project team also evaluated hydromechanical aspects of CO_2 injection that could potentially affect the expected pressure buildup and brine migration characteristics. Geomechanical modeling was conducted using the coupled reservoir-geomechanical simulator TOUGH-FLAC (Transport Of Unsaturated Groundwater and Heat-Fast Lagrangian Analysis of Continua), which was recently enhanced to study the coupled multiphase flow and geomechanical conditions associated with underground injection of CO_2. Example applications include simulation of fault-slip behavior for a discrete fault in an aquifer-caprock system to assess maximum sustainable injection pressure, and evaluation of tensile and shear failure in response to CO_2 storage in a multilayered geological system.

The analytical and numerical studies that the team conducted for idealized geological settings proved very beneficial to gain a general understanding and to study respective sensitivities. The team's results demonstrated the importance of evaluating the hydrologic perturbations generated by CO_2 storage, suggesting that any site assessment should consider the constraints imposed by pressure perturbation and brine displacement, either to avoid shallow-water impacts in open systems or to account for pressure constraints in closed systems. When investigating these issues, it is important to consider not just the storage formation, but also the multilayer characteristics of the site. Of course, certain model simplifications and parameter choices made above may be inadequate at given storage sites. Thus, the systematic simulations conducted for idealized formations were followed by site-specific modeling of two regional basins, which had been selected for three main reasons: (1) they are located in regions with a large portfolio of existing and potential future CO_2 point sources, (2) they contain formations potentially suitable for sequestering large volumes of CO_2, and (3) they contain a variety of inter- and intra-basin hydrogeological conditions, some subset of which is likely to be encountered at most high-capacity sequestration sites.

The two site-specific real-world applications are the Illinois Basin and the San Joaquin Basin in the California Central Valley. The Illinois Basin allows the team to investigate pressure buildup and brine displacement in large open marine sediment, with continuous sealing units and few known fault zones. The San Joaquin Basin was chosen to investigate the environmental impact of geologic carbon sequestration in fault-compartmentalized sandstone, representing a potential closed system. While the Illinois Basin study has been finalized, the California Central Valley study is ongoing and will be finalized in the first quarter of 2010.

The numerical model developed for the Illinois Basin is the first regional-scale three-dimensional simulation model that can capture both the local-scale CO_2-brine flow processes and the large-scale groundwater flow patterns in response to multiple CO_2 storage projects. The model domain covers an area of roughly 570 km by 550 km, a total area of 241,000 km^2, yet due to innovative gridding and high-performance simulation techniques this domain allows for local-scale simulations at a resolution of a few meters. A three-dimensional unstructured mesh was constructed with progressive mesh refinement to capture details of two-phase flow and its spatial variability, using local grid refinement down to 20 m in the horizontal and 10 m in the vertical direction in the vicinity of individual CO_2 storage locations within the basin. Predictive models like this one developed for the Illinois Basin provide a powerful tool for coordinating and managing several storage projects located in one large basin.

The project's regional-scale model was applied to a hypothetical future carbon sequestration scenario in the Illinois Basin in the Midwestern United States. This area hosts a significant number of large, stationary CO_2 emitters and will be one of the most important regions for geologic storage of CO_2 in the United States. The team's simulations assumed that each of the 20 individual storage projects spread out in the center of the basin will inject 5 megatons (Mt) of CO_2 per year into the Mount Simon formation over a time period of 50 years. The total annual injection mass of 100 Mt corresponds to roughly one-third of the current annual CO_2 emissions from stationary sources in the area. The team's predictions demonstrate that multiple-site storage in the Mount Simon formation may result in a large continuous region with overpressure, in which the pressure perturbations from one storage site can strongly interfere with other storage sites. With respect to far-field impacts, pressure changes may propagate as far as 200 km from the core injection area hosting the 20 storage sites. While this pressure buildup and associated brine migration is not likely to impact neighboring basins, the potential for hydrogeologic and geochemical changes in the overlying groundwater regimes requires further evaluation. For example, salinity issues could become a concern if brackish water from the Mount Simon formation is pushed upward into overlying freshwater aquifers via potential localized pathways, such as conductive faults or open boreholes. Conclusions drawn from the Illinois basin predictions and from modeling simplified geologic systems point to the importance of achieving reliable large-scale predictions of hydrogeologic impacts in response to CO_2 storage, the need to better quantify the possibility of groundwater impacts from large-scale pressure changes in deep storage reservoirs, and the advantage of having suitable pressure management schemes for controlling pressurization and brine displacement. These three issues inform the research goals for the next project phase.

RESEARCH PLANNED FOR NEXT BUDGET PERIOD

Considering the relevance of the observed basin-scale hydrologic impacts, the team will continue to work on the large-scale hydrological and environmental impacts of CO_2 geological storage in FY2010 through FY2012. The project continuation will address three topics: (1) better predictive assessment of brine pressurization and migration on the basin scale (model confidence), (2) better understanding of the possible consequences of far-field pressurization on groundwater resources to provide the technical basis for Area-of-Review assessment (impact assessment), and (3) development and optimization of pressure management schemes to improve CO_2 storage potential and remediate CO_2 leakage (management and mitigation).

Topic 1: Improve Understanding and Prediction Reliability of Basin-Scale Brine Pressurization and Migration (Model Confidence). It is important to ensure that the processes and parameters driving large-scale pressure buildup are well understood and that uncertainties are quantified and minimized. The team's planned research includes sensitivity analysis and data review to identify and constrain the most sensitive parameters, high-resolution modeling studies to account for small- and intermediate-scale heterogeneity, and detailed modeling of a selected analog or demonstration site with plenty of near- and far-field pressure data.

Topic 2: Evaluate the Impact of Brine Pressurization on Groundwater Resources and Provide Technical Basis for Area-of-Review Determination (Impact Assessment). While the project's past research has focused on determining the large-scale pressure changes and brine migration within deep reservoirs, the goal now is to determine the possible consequences of far-field pressurization on groundwater resources under various conditions. This research will help to assess whether groundwater vulnerability may be a limiting factor to storage capacity in a given area. It will also provide the technical basis for defining the extent of an Area of Review for permitting of CO_2 storage projects. The project team will evaluate the potential for and magnitude of upward brine migration into freshwater aquifers through fast-flow pathways (leaky faults and open boreholes) between deep storage formations and freshwater aquifers. This task includes the development of interaction scenarios that determine how deep formations interact with shallow potable groundwater resources, and predictive modeling studies that evaluate brine leakage rates into freshwater aquifers for selected scenarios.

Topic 3: Evaluate Pressure Management Schemes via Brine Extraction (Management and Mitigation). Creative pressure management schemes can be used to lower pressure-related constraints on storage capacity and to remediate CO_2 leakage; pressure management is particularly important during the full-scale deployment phase of geologic carbon sequestration (GCS). These schemes involve extraction of resident brine from storage formations and re-injection into overlying/underlying saline aquifers, or pressure-driven brine transfer from storage formations to overlying saline formations. In this task, the technical feasibility of pressure management schemes will be evaluated for geologic sequestration, and the fundamental issues and potential merits of the suggested pressure manipulation schemes will be investigated by means of numerical simulations for hypothetical injection scenarios. The subtasks include development of a suite of possible pressure management options, design and optimization of pressure management strategies via numerical modeling, application of feasible pressure management options to a real-world example, and the development of a guidance document on pressure mitigation options.

Relationship to Program:

This project will support important system-modeling advances within the simulation and risk assessment pathway of the NETL Carbon Sequestration Program. The main benefit of this project is that it will provide DOE with a thorough understanding of one of the most important issues of scaling up CO_2 storage to full-scale deployment: the issue of large-scale pressure buildup and brine displacement, and the subsequent effects on hydrogeological systems. Predictive tools are being developed and utilized, assessments are being conducted for real-world applications, and possible management/mitigation methods are being evaluated. This project's specific focus on the possible environmental impacts of pressure buildup and brine displacement on groundwater resources is particularly relevant because the draft regulation for geologic carbon sequestration under the Safe Drinking Water Act developed by the U.S. Environmental Protection Agency (EPA) has its main focus on protecting underground sources of drinking water from injection-related activities. The research conducted in this project will provide a technical background that can be very useful to inform EPA efforts to develop a reasonable regulation approach for CCS. In fact, EPA's Notice of Data Availability related to the draft regulation for GCS wells makes frequent reference to this research project.

Primary Project Goal:

The goals of this project are to improve the understanding of and prediction capability for large-scale hydrological impacts of CO_2 storage in deep saline reservoirs; determine the potential impacts on groundwater resources and related implications on storage capacity; and develop pressure-management schemes for minimizing large-scale hydrological impacts.

Objectives:

FIRST BUDGET PERIOD: FY2007 THROUGH FY2009

The tasks and related objectives, summarized from the initial project plan, are listed below.

Task 1: Evaluate Storage Capacity and Pressure Buildup in Idealized Pressure-Constrained Storage Formations (Closed Systems)

- Develop analytical and numerical solutions that allow for the fast evaluation of brine displacement by injected CO_2 and the related pressure buildup in simplified geological systems.
- Develop a basic understanding of potential pressure buildup in closed systems and determine the sensitivity of pressure buildup and storage capacity to injected volume, formation size, hydraulic properties, and other key parameters.

Task 2: Evaluate Pressure Buildup and Brine Displacement in Idealized Multilayered Groundwater Systems (Open Systems)

- Conduct a semi-analytical or numerical simulation study to evaluate the brine displacement by injected CO_2 and the related pressure buildup in a multilayered geological system.
- Develop a basic understanding of the potential pressure buildup in a laterally open storage formation and explore the effects of interlayer communication through low-permeability seals.

Task 3: Hydromechanical Aspects of Injection in Idealized Multilayered Groundwater Systems

- Evaluate the role of mechanical deformation, with associated permeability changes, and identify related data needs.

Task 4: Analysis and Modeling of One or Two Regional Groundwater Systems

- Conduct a modeling evaluation of one or two regional groundwater systems in response to CO_2 injection. Two deep saline aquifer systems, the Illinois Basin in Illinois and adjacent states, and the Southern San Joaquin Basin in California, have been chosen based on interaction with regional partnerships.
- Evaluate pressure buildup and brine displacement for these real-world examples.

All project milestones for the first budget period have been achieved on schedule, with the exception of Task 4. Modeling of the second real-world basin (California Central Valley) is ongoing and will be finalized in the first quarter of 2010, without extra cost. This schedule revision, which was communicated early with the NETL project manager William O'Dowd, was due to delays in receiving data input from the West Coast Regional Carbon Sequestration Partnership.

SECOND BUDGET PERIOD: FY2010 THROUGH FY2012

The continuation of this project through FY2012 has three main objectives, organized in three topics: improving the prediction reliability of basin-scale models (model confidence), quantifying the potential impact of brine pressurization and migration on groundwater resources (impact assessment), and evaluating pressure management schemes via brine extraction (mitigation). These topics will include several tasks and related objectives (as summarized from the project continuation proposal), outlined below. The topics are independent of each other, such that project success in one area is not affected by progress in another area.

Topic 1: Improve Understanding and Prediction Reliability of Basin-Scale Brine Pressurization and Migration (Model Confidence)

a. Conduct sensitivity analysis to identify the most sensitive parameters (e.g., pore compressibility, permeability, and porosity) and constrain these through a detailed literature and data review.
b. Conduct high-resolution modeling studies of small- and intermediate-scale heterogeneity in permeability (e.g., sand-shale beds, internal layering, and faults) to better understand pressure propagation in complex geologic environments; and develop upscaling approaches.
c. Perform data analysis and detailed modeling of a selected site with plenty of near- and far-field pressure data (either from an industrial natural analog or a large-scale Regional Carbon Sequestration Partnership Phase III project).

Topic 2: Evaluate the Impact of Brine Pressurization on Groundwater Resources and Provide technical Basis for Area-of-Review Determination (Impact Assessment)

a. Develop scenarios for how deep formations interact with shallow potable groundwater resources.
b. Conduct predictive modeling studies to evaluate brine leakage rates into freshwater aquifers for selected scenarios.
c. Develop a framework for Area-of-Review determination.

Topic 3: Evaluate Pressure Management Schemes via Brine Extraction (Mitigation)

a. Develop a suite of possible pressure management options, including extraction and use, extraction and re-injection, and pressure-driven wellbore flow from storage formations to overlying formations.
b. Design and optimize pressure management strategies (i.e., well patterns, withdrawal rates and duration, cost estimates) via numerical modeling for hypothetical injection scenarios and different management options.
c. Apply pressure management options to a sedimentary basin with a developed basin-scale model.
d. Develop a guidance document on pressure mitigation options and design.

07: FWP-ESD09-056 Task 2

Project Number	**Project Title**			
FWP-ESD09-056 Task 2	GEO-SEQ			
Contacts DOE/NETL Project Mgr.	**Name** Karen Cohen	**Organization** NETL – Carbon Sequestration Division	**Email** karen.cohen@ netl.doe.gov	
Principal Investigator	Barry Freifeld	Lawrence Berkeley National Laboratory	BMFreifeld@lbl.gov	
Partners	BP, Sonatrach, and Statoil In Salah Joint Venture CO2CRC – Cooperative Research Centre for Greenhouse Gas Technologies Kevin Knauss (now at LBNL) formerly Lawrence Livermore National Laboratory David Cole & Tommy Phelps, Oak Ridge National Laboratory Texas Bureau of Economic Geology Yousif Kharaka, United States Geological Survey			
Stage of Development				
__Fundamental R&D	__Applied R&D	X Proof of Concept	__ Prototype Testing	__Demonstration

Technical Background:

MOTIVATION

The GEO-SEQ Project has two primary goals: (1) to develop ways to improve predictions of injectivity and the capacity of saline formations and depleted gas reservoirs, and (2) to develop and test innovative high-resolution methods for monitoring carbon dioxide (CO_2) in the subsurface. The GEO-SEQ project leverages scientific understanding and technology development through leadership and collaboration with three highly visible world-class (Carbon Sequestration Leadership Forum-recognized) geologic CO_2 storage projects. The three projects are the Frio Brine Pilot tests; the Otway Project; and the In Salah Industrial-Scale CO_2 Storage Project. At the time of this review, the Frio Brine Pilot test has been concluded and the results have been widely disseminated in peer-reviewed journal publications.

GEO-SEQ has led the development of downhole fluid and gas sampling by U-tube; downhole Continuous Active Source Seismic Monitoring (CASSM); and reservoir simulation capabilities including reactive geochemistry, multicomponent gas mixture behavior, and geomechanical coupling. In future years, the project team will continue to advance understanding of CO_2 migration in brine formations and depleted gas reservoirs, investigate geomechanical effects of industrial-scale CO_2 injection, and develop novel laboratory measurements of petrophysical properties at in situ conditions. Advances derived from GEO-SEQ efforts also support DOE Regional Carbon Sequestration Partnerships (RCSP) projects through the involvement of the investigators in various partnership projects; technology advancements will likely be used in commercial-scale CO_2 operations in the future.

MAJOR IMPACTS OF THE GEO-SEQ PROJECT

- The Frio Brine Pilot tests have set a standard for imaging and monitoring of a CO_2 plume. Numerous additional projects have come to the Frio project team for guidance on the design and development of an effective monitoring program.
- As a consequence of the Interferometric Synthetic Aperture Radar (InSAR) results as part of the In Salah joint industry project (JIP), the entire

monitoring strategy at the Krechba Field has been reevaluated and InSAR has become a major element within the CO_2 monitoring program.

- The Otway Project has just completed the Stage I injection of 65,445 tonnes of gas into the Waarre C formation. The Lawrence Berkeley National Laboratory (LBNL)-designed multifunctional completion in the Naylor-1 borehole has facilitated the acquisition of two years of detailed geochemical and geophysical data. As such, the first detailed look at the filling of a depleted gas reservoir has generated a wealth of data to help guide future storage projects. LBNL continues to highly leverage the research at the Otway Basin by working with CO2CRC to conduct a detailed appraisal of the Parratte Formation for CO_2 storage; this appraisal is being accomplished using a single-well huff n' puff test program to estimate formation properties critical to estimating storage capacity.

References to technology and monitoring protocols developed under the GEO-SEQ research program appear in the NETL manual "Monitoring, Verification, and Accounting of CO_2 Stored in Deep Geologic Formations;" technical addendums to the U.S. Environmental Protection Agency proposed rule under 40 Code of Federal Regulations (CFR), Parts 144 and 146 for CO_2 storage; and the International Energy Agency greenhouse-gas-monitoring guidance.

ACCOMPLISHMENTS TO DATE

As a mature program, GEO-SEQ has diverse accomplishments relating to the prediction, monitoring, and verification of geologic carbon storage in saline formations and depleted gas reservoirs. Accomplishments during the three years presented in this review include the development of innovative laboratory methods for petrophysical investigation (split-Hopkinson resonant bar apparatus), the deployment of multifunction well-based monitoring instrumentation packages as part of domestic and international demonstration programs, and the groundbreaking use of InSAR for CO_2 plume monitoring.

The approach for GEO-SEQ has been to identify gaps and critical needs relating to the monitoring and verification of CO_2 storage, starting with fundamental research to understand the issues fully and progressing to mature technology to test the concept as part of field-scale CO_2 sequestration demonstration projects. This is carried out in an iterative fashion, since lessons learned from field testing then guide future theoretical and laboratory-scale efforts.

FRIO BRINE PILOT TESTS

As part of the fiscal year 2007 (FY2007) through FY2009 review period, the second Frio Brine Pilot built on the success of the initial Frio injection test, which was conducted in 2004. The initial test, consisting of a 1,600-tonne injection into the Frio "C" sand, was groundbreaking in its deployment of an integrated wellbore system for CO_2 plume imaging, incorporating simultaneous monitoring of geochemical, hydrological, and geophysical parameters. Results for the test were presented through dozens of presentations at scientific conferences and research workshops.

At the same location in Liberty County, Texas, a second injection test in the Frio "Blue" sand was conducted at a depth of 1.6 km. The second test incorporated a new concept in downhole real-time CO_2 monitoring: CASSM. A CASSM survey is conducted using cross-well geometry, with a piezoelectric source incorporated in one well and a hydrophone array in a second well. As the injected CO_2 crosses the seismic raypaths created by the source-receiver pairs, the changes in amplitude and phase can be used to estimate CO_2 saturation. The engineering of a piezoelectric source that could be deployed around a fixed production tube and operated simultaneously with other instrumentation led the LBNL team to apply for a U.S. patent. The field testing at Frio was concluded in FY2009 with the acquisition of a final vertical seismic profile (VSP), followed by the plugging and abandonment of the test wells.

AUSTRALIAN CO2CRC OTWAY PROJECT

The Otway Project is the world's first demonstration project for the storage of CO_2 in a depleted gas field with a comprehensive monitoring program to understand the detailed processes by which CO_2 enters a formerly produced gas cap. Led by the Australian CO2CRC and in collaboration with LBNL, the project deployed a well-based monitoring program, building upon the innovations from both Frio Brine Pilot tests. The hydrological, geochemical, and geophysical monitoring system installed in the Naylor-1 well consisted of (1) nine vertical component geophones for VSP monitoring, three 3-component geophones for microseismic monitoring, and a set of three hydrophones and three geophones for high-resolution travel-time monitoring within the gas reservoir; (2) two pressure/temperature sensors; and (3) three U-tube geochemical samplers. In September 2007, this complex string was installed by CO2CRC and LBNL staff working together with the site operator, AGR Asia-Pacific. Weekly U-tube sampling and periodic geophysical surveys were conducted by staff from Deacon University and Curtin University, respectively. Injection of CO_2-rich gas, produced from the nearby Buttress-1 well, commenced in March 2008 into the CRC-1 well, located 300 m downdip from the Naylor-1 well. Injection was halted at the end of August 2009 with the introduction of 65,445 tonnes of gas.

Though data collection is ongoing, an incredibly rich data set has already been collected, and interpretation of the data is ongoing by both LBNL and CO2CRC. The microseismic monitoring data indicates minimal acoustic response to the injection, and VSP data indicates no leakage into the overlying Belfast Mudstone. These null results were expected, given the overall integrity of the reservoir and modest pressure changes; and they can assure the public that the reservoir is capable of safely storing the injected volumes of CO_2. The multilevel U-tube geochemical sampling system has provided answers to some of the primary scientific questions that were unresolved when the testing commenced. At the onset of the study it was unknown if buoyancy would lead to segregation of the injected fluid from the overlying gas cap, or whether stratigraphic heterogeneity would allow the denser injected CO_2 to move up into the methane-filled gas cap. The multilevel monitoring system was able to reveal the detailed dynamical response of the reservoir as it filled with the injected gas, indicating where the injected gas first arrived at the gas-water contact interface and eventually resulting in a push down of the gas-water contact. Eventually, injected gas mixed throughout the overlying gas cap and the lowering of the gas-water contact resulting in the two U-tubes beneath the gas-water contact to become self-lifting with gas. The analysis of tracers (perdeuterated methane [CD_4], krypton [Kr], and sulfur hexafluoride [SF_6]) added to the injected gas is ongoing, with differences in tracer transport from the injected gas indicating relative amounts of gas-water interaction.

IN SALAH JIP

Berkeley Laboratory's work as part of the In Salah JIP includes assessments of site geological and geomechanical data, microseismic monitoring, geomechanical simulation of horizontal well injection, and an investigation of satellite-based interferometry (i.e., InSAR) data for detection of surface deformation.

In spring 2007, a preliminary reservoir geomechanical analysis by the LBNL GEO-SEQ team indicated that surface deformations on the order of centimeters would be feasible. As a result, it was decided to explore the possibility of using the satellite-based interferometry (i.e., InSAR) for detecting ground surface deformations related to the CO_2 injection. InSAR data was acquired and analyzed by Tele-Rilevamento, using a state-of-the-art permanent scatterer method enabling determination of mm-scale surface deformations. The results presented in Vasco et al. (2008a, b) were remarkable, because the observed uplift could be clearly correlated with each injection well (with uplift bulges several km in diameter centered around each injection well). Measured uplift occurred within a month after start of the injection and the rate of uplift was approximately 5 mm/year, amounting to about 1.5 cm in the first three years of injection. One reason for the success of the InSAR technology at Krechba is the fact that the ground surface consists of relatively hard desert sediments and bare rock, which do not have problems with movements of loose sediments or vegetation.

Relationship to Program:

This project will support important high-resolution monitoring advances within the monitoring, verification, and accounting pathway of the NETL Carbon Sequestration Program. The primary benefit of the GEO-SEQ effort is that as CO_2 storage projects transition from pre-commercial to commercial scale, monitoring tools and techniques will have been rigorously tested as part of scientifically controlled demonstration programs. Appropriate monitoring and validation techniques, often differing from standard practices in the oil and gas industries, will have a track record under real-world conditions. The benefits and drawbacks of each monitoring method would have been considered in a transparent process, which culminated in peer-reviewed dissemination of research results. This will provide assurance to both the public and regulatory agencies that CO_2 storage is something that can be carried out safely and will allow commercial operators to select appropriate monitoring technology with reduced risk.

Primary Project Goal:

The primary project goal is (1) to develop ways to improve predictions of injectivity and the capacity of saline formations and depleted gas reservoirs, and (2) to develop and test innovative high-resolution methods for monitoring CO_2 in the subsurface by leveraging highly visible world-class geologic CO_2 storage demonstration projects.

Objectives:

SUBTASK 2.1. FUNDAMENTAL PROCESS AND RESPONSE STUDIES

This new task has grown out of previous work to support field-scale investigation at pilot projects (In Salah, Otway, and Frio). The project team's work over the last several years revealed that integrating field measurements with numerical reservoir modeling requires better understanding of certain key fundamental processes (petrophysics and geochemical transport) that come from supporting laboratory measurements. Additionally, the integration of laboratory and field measurements needs improvement and support. Recognizing these needs, the

LBNL team will focus a GEO-SEQ task in this critical area. This task is supplanting the previous Frio Brine Pilot task, which has now ended.

The Fundamental Process and Response Studies will include laboratory measurement of petrophysical responses (e.g., seismic velocity as a function of partial CO_2 saturation at in situ conditions) and geochemical transport processes (e.g., measurement of Henry's coefficients at in situ conditions) to allow improved analysis of field studies such as seismic monitoring and tracer breakthrough analysis. The project team also plans to work on improved integration of reservoir models (TOUGH2 [Transport Of Unsaturated Groundwater and Heat]) with field monitoring data and to support development of key monitoring technologies (initially targeting the CASSM technique).

Subtask 2.1.1 Petrophysical laboratory measurements. Following initial construction and safety evaluation of the split-Hopkinson resonant bar apparatus in FY2009, the LBNL team has a plan for testing using core samples from field sites (e.g., Frio, Otway, RCSP sites). The plan tasks include the following:

- Calibration tests using synthetic samples
- Refinement of Moduli/Q inversion code parameters
- Calibration tests using reference rock samples (room temperature, low-medium confining stress) and unconsolidated granular media
- Medium-pressure tests using field core samples (<3,500 lb per square inch [psi] confining stress)
- High-pressure tests using field core samples (<5,000 psi confining stress)

Subtask 2.1.2. Laboratory phase-partitioning tracer studies. There is considerable interest in the benefits of co-injecting phase-partitioning tracers with CO_2 to better understand CO_2 trapping mechanisms. Data sets for phase-partitioning tracers such as Kr, Xenon (Xe), and SF_6, have already been collected during the Frio Brine Pilot, and are also planned for collection during the WESTCARB (West Coast Regional Carbon Sequestration Partnership) and SECARB (Southeast Regional Carbon Sequestration Partnership) phase II and III demonstration programs. While there is detailed data for the phase-partitioning behavior of these compounds in air-water systems, there is no laboratory data to detail their behavior in CO_2/brine systems. This task will aim to determine phase-partitioning tracer behavior at the pressure and temperature conditions of demonstration programs and will support the interpretation of field data.

Subtask 2.1.3. Coupled reservoir modeling and field monitoring. Integration of reservoir models (i.e., TOUGH2) for field sites with field monitoring data is currently being done on an ad-hoc basis. The LBNL team plans to streamline this integration and work toward a coupled inversion. Additionally, they propose to work on increasing the scale of modeling and monitoring from initial pilot experiments, eventually reaching basin scale. As sequestration efforts move from pilot scale to industrial scale, the effects on entire basins need to be considered in monitoring and modeling programs. This subtask will support development of basin-scale monitoring programs that can be coupled with basin-scale reservoir models. At the basin scale, properties such as pressure fronts and brine migration become important to sequestration monitoring and modeling.

Subtask 2.1.4. Monitoring technology development. As GEO-SEQ has developed real-world experience in monitoring sequestration pilots, certain technologies have been developed which have proved useful (e.g., the U-tube fluid sampler and the piezo-tube seismic source for CASSM-type experiments). The project team has planned a small effort to document and further develop these technologies, beginning with the piezo-tube source for CASSM experiments.

SUBTASK 2.2 OTWAY PROJECT

The GEO-SEQ objective for participating in the Otway Project is to leverage the investment of Australia's CO2CRC research program in a world-class field test of sequestration in a depleted gas field.

Subtask 2.2.1 Field testing. The project team will continue to work with CO2CRC to carry out the Stage I injection test into the Waarre C depleted gas formation, supporting field tests and interpreting collected data. As more data is collected, CO2CRC and LBNL will coauthor papers for peer-reviewed publications. Early in Q2 FY2010, CO2CRC is scheduled to begin drilling for the Stage II injection test in the saline Parratte Formation. LBNL will play a central role in the design and fabrication of the equipment for carrying out the Stage II testing program.

Subtask 2.2.2 Laboratory measurements. Using the equipment developed under subtask 2.1.1, the project team will perform laboratory measurements of seismic properties of Otway core. These studies will be conducted at variable CO_2 saturations and at in situ pressures and temperatures.

Subtask 2.2.3 Modeling and simulation. This task will cover both reservoir-modeling support for the planning of the Stage II injection test as well as interpretation of the U-tube data acquired in Stage I. The TOUGH2 code with the equation of state module EOS7c will be used to simulate the behavior of the Otway Basin CO_2/methane/brine system.

Subtask 2.2.4 Planning and coordination. Given the size and complexity of the Otway Project, considerable effort goes into coordinating the numerous research groups, acquiring different data sets, and reporting requirements to different government entities. LBNL will continue to support CO2CRC by participating in planning teleconferences and meetings, workshops, peer reviews, Research Advisory Committee meetings, and requests for information.

SUBTASK 2.3 IN SALAH INDUSTRIAL-SCALE CO_2 STORAGE PROJECT

The GEO-SEQ objectives of the research related to the In Salah Industrial-Scale CO_2 Storage Project are (1) to assess the effectiveness of CO_2 storage in low-permeability formations using long-reach horizontal injection wells, and (2) to investigate monitoring techniques to evaluate the performance of a high-pressure CO_2-injection operation. During FY2010, it is expected that CO_2 injection will resume in one of the three injection wells, well KB502, which has been shut down for more than a year. LBNL will analyze and model both induced seismicity and surface uplift, and then tie this analysis to measured data.

Subtask 2.3.1 Reservoir data collection. The project team will continue close interaction with BP to acquire field data necessary for their modeling efforts.

Subtask 2.3.2 Analysis of ground surface deformations from InSAR. The In Salah JIP will acquire new satellite data focusing on the time period for the resumed injection at KB502. These data will allow for evaluation of three-dimensional displacement (rather than just subvertical). LBNL will analyze this new data to invert for subsurface fluid movements.

Subtask 2.3.3 Simulation of near-field injection processes. The dual-continuum hydromechanical model developed within this task for considering stress-dependent permeability in fractured rock masses will be further improved to consider stress-induced changes in retention properties and relative permeabilities. This is important for the multi-phase flow properties in the reservoir and for the sealing performance of the caprock under injection-induced stress changes.

Subtask 2.3.4 Seismic monitoring and analysis. LBNL has installed microseismic equipment in a 500-mdeep borehole close to injection well KB502. Thus, microseismic activity and ground surface deformation will be closely monitored when resuming injection at KB502. LBNL will analyze microseismicity for location and source mechanisms.

Subtask 2.3.5 Simulation of large-scale deformation and stress changes. The fully coupled fluid flow and geomechanical analysis will be extended to look at the potential for induced microseismicity associated with resuming KB502 injection. Moreover, the potential effects of cooling shock near the wellbore will be studied. The injection-induced cooling will be calculated based on the results of downhole temperature and pressure from LBNL's wellbore simulation that was conducted during FY2009.

SUBTASK 2.4 GEOCHEMICAL ASSESSMENT FOR CO_2 STORAGE PERMANENCE, ACCOUNTING, AND WELL-PERMITTING ISSUES (HEAVY METAL/ORGANIC RELEASE AND RESERVOIR/CAPROCK INTEGRITY)

The primary objective of the proposed work is to provide geochemical components of a methodology for assessing the appropriateness of proposed saline reservoirs and depleted oil reservoirs (including those combining CO_2 storage with Enhanced Oil Recovery) for large-scale CO_2 injection with respect to the permanence of sequestration over potentially long time periods (~10,000 years in the case of Class I wells and, as of yet, unspecified but similarly long periods per 40CFR144) and expanded Areas of Review. Both geochemical and hydrologic appropriateness of each site must be assessed because the processes are coupled through reactive transport mechanisms. A secondary objective of this research is to address the need to assess the geochemical appropriateness of proposed commercial-scale (Regional Partnership and others) CO_2 injection sites in a time frame that will allow rapid permitting of these sites. Objectives will be achieved using a combined laboratory experiment/field sampling/reactive transport modeling approach. The geochemical components of a standard operating procedure for assessing CO_2 storage performance and reservoir chemistry to determine suitability for commercial scale operations in saline formations and depleted oil reservoirs will be a product of this research.

The project team uses a combined experimental- and simulation- (computer modeling) based iterative approach to geochemical research. To study coupled processes occurring near equilibrium, low flow/no flow conditions, ion exchange or adsorption/desorption reactions, and thermodynamic (solubility) measurements made at equilibrium, the LBNL team uses closed, flexible gold-bag systems referred to as Dickson bombs. Multiple fluid samples can be acquired throughout a run without disturbing the temperature and pressure of the experiment. Fluid samples are analyzed for major and trace cations using Inductively Coupled Plasma-Emission Spectrometry (ICP-ES) and ICP-Mass Spectrometry (ICP-MS), if necessary. Anions are analyzed using ion chromatography. Gas samples may be acquired and analyzed for CO_2 present, as either a separate phase or dissolved in the aqueous fluid, using an infrared CO_2 analyzer. The post-test solid analyses used to determine both dissolution of primary phases and growth of secondary phases include x-ray diffraction for major components and vertical scanning interferometry (VSI) (i.e., the Wyko NT3300 interferometer) for nano- to micro-scale surface analyses.

08: DE-NT0006642

Project Number NT0006642	**Project Title** Shallow Carbon Sequestration Demonstration Pilot			
Contacts DOE/NETL Project Mgr.	**Name** William O'Dowd	**Organization** NETL – Carbon Sequestration Division	**Email** William.ODowd@ netl.doe.gov	
Principal Investigator	Gary J. Pendergrass	City Utilities of Springfield	gary.pendergrass@ cityutilities.net	
Partners	Missouri University of Science and Technology, Missouri State University, Missouri Department of Natural Resources			
Stage of Development				
__ Fundamental	X Applied R&D	__ Proof of Concept	__ Prototype Testing	__ Demonstration

Technical Background:

As most of the power plants in Missouri use coal as their energy source, City Utilities of Springfield (CU) and others have pursued measures to reduce the impact of carbon emissions. Projects funded by NETL are focusing on the injection of supercritical carbon dioxide (CO_2) into deep wells located in Illinois and North Dakota, among other states, and results to date indicate that this can be an effective mechanism for the sequestration of carbon emissions from coal-fired power plants.

Unfortunately, Missouri lacks the large, deep, geological basins, such as the Williston, Illinois, and Appalachian Basins, that are available for carbon sequestration in other parts of the country. Missouri's geology is dominated by a broad uplift, the Ozark Dome. Sedimentary stratum in the state rarely exceeds 2,400 ft in depth, except within the Forest City Basin in the extreme northwestern corner of the state. Based on research to date, the Lamotte Sandstone appears to provide the best opportunity in the state for carbon sequestration. Since the Lamotte is the basal sedimentary unit in Missouri, its depth is generally not sufficient for supercritical injection. This formation is relatively saline, provides very low yields, and is not generally utilized as a water supply aquifer in the state. It is persistent across the state, and is absent only in the St. Francis area, where Precambrian rock is exposed, as well as in a few isolated pockets around the state. Thickness of the Lamotte ranges from around 100 ft along the western border to more than 400 ft along the Mississippi River.

In 2006, CU commissioned the University of Missouri-Rolla (now Missouri University of Science & Technology) to perform an analysis of existing Lamotte core from an exploration well in Dade County, Missouri. They found that the Lamotte exhibited porosity and permeability comparable to oil and gas reservoirs and concluded that the formation holds promise for carbon sequestration.

In southwestern Missouri, the Lamotte is overlain by the Bonneterre Formation, a sandy dolomite that is considered part of the sequestration target for the purposes of this pilot demonstration. Above the Bonneterre are the Davis and Derby-Doerun Formations, which consist of interbedded dolomite, siltstone, and shale and function together as a confining layer between the Bonneterre and the Ozark Aquifer. The rock units that comprise the Ozark Aquifer include the Potosi

Dolomite, Eminence Dolomite, Gunter Sandstone, Gasconade Dolomite, Roubidioux Sandstone and Dolomite, Jefferson City Dolomite, and Cotter Dolomite. The Northview Shale functions as a confining layer between the Ozark Aquifer and the shallower Springfield Aquifer. The rock units that comprise the Springfield Aquifer include the Pierson Limestone, Reeds Spring Limestone, Elsey Limestone, and Burlington Limestone. The Missouri Department of Natural Resources generally requires water supply wells to be cased through the Northview shale.

If shallow gas-phase sequestration proves to be a viable option, then on-site injection of CO_2 at individual power plant sites will be the most efficient and cost effective means to address carbon regulation.

In 2007, CU met with other Missouri electric utilities to discuss a pilot demonstration of carbon sequestration in the Lamotte Formation. The Southwest Power Station (SWPS) in Springfield was selected as the site for this project. SWPS is located in a suburban area at the southwestern edge of the City of Springfield and, along with the adjacent Southwest Sewage Treatment Plant, encompass approximately 1,500 acres. SWPS Unit 1 was constructed in the 1970s and utilizes three water supply wells in the Ozarks Aquifer for cooling and makeup water. The first exploratory boring completed on-site penetrated the full thickness of the Lamotte and bottomed in the Precambrian basement rock. The log for this boring showed the top of the Bonneterre at a depth of 1,795 ft and the base of the Lamotte at a depth of 2,125 ft, yielding a combined target thickness of 330 ft. The well log also shows that a high percentage of both the Lamotte and Bonneterre are composed of sand. Packer testing performed during exploration confirmed that the Lamotte provided insufficient yield for water supply and that the Davis/Derby-Doerun Formation functioned as a confining layer. Therefore, the geological characteristics of the SWPS site appear to be appropriate for assessing the potential for carbon sequestration in the Lamotte Formation.

The Shallow Carbon Sequestration Demonstration Project described herein is being conducted by a team of scientists, engineers, consultants, and graduate students from CU, the Missouri University of Science and Technology, Missouri State University, and the Division of Geology and Land Survey of the Missouri Department of Natural Resources.

Relationship to Program:

This project will advance knowledge of the feasibility of on-site carbon sequestration at Missouri power plant sites as part of the storage pathway of the NETL Carbon Sequestration Program.

Some of the benefits of successful project completion include the following:

1. Potential for the implementation of on-site shallow carbon sequestration at SWPS in Springfield, MO
2. Potential for further studies to confirm the feasibility of on-site shallow carbon sequestration at other coal-fired power plants in Missouri and beyond
3. Reduced costs for the implementation of carbon sequestration at coal-fired power plants
4. The creation of additional jobs at coal-fired power plants to design, construct, and operate on-site carbon sequestration processes

Primary Project Goal:
The primary project goal is to assess the suitability of the Lamotte Sandstone for shallow carbon sequestration.

Objectives:

1. *Determine the reservoir properties of the Lamotte Formation.* The project team will conduct a three-dimensional seismic survey; complete downhole geophysical logs; perform formation pressure and fracture tests; analyze the gas permeability of core samples; determine the fluid injection profile; and monitor the lateral migration of CO_2 injected into the formation.
2. *Determine the competency of the Davis/Derby-Doerun confining layer.* The project team will complete a three-dimensional seismic survey, an analysis of the porosity and permeability of retrieved core samples, downhole geophysical logs, packer interval pressure testing, and post-injection monitoring of Ozark Aquifer cooling water-supply wells.
3. *Determine the optimum sustainable injection rate of CO_2 into the Lamotte Formation.* The project team will test injection rates in a bench-scale reactor using retrieved core samples, develop a reservoir model, and inject a limited quantity of food-grade CO_2 into the formation.
4. *Evaluate trapping mechanisms that result from gas-phase injection of CO_2 into the Lamotte Formation through bench tests or core samples.* The project team will conduct bench-scale reactor tests to determine the rate, type, and extent of mineralization and conduct post-injection monitoring of the wells within the target formation.

09: FWP-FEW-0174 Task 3

Project Number	**Project Title**			
FWP-FEW-0174 Task 3	Injection & Reservoir Hazard Management: Fault Geomechanics and Integrated CO_2 Leakage Simulation Applied to Geologic Storage			
Contacts	**Name**	**Organization**	**Email**	
DOE/NETL Project Mgr.	Andrea McNemar	NETL – Carbon Sequestration Division	Andrea.McNemar @ netl.doe.gov	
Principal Investigator	Walt McNab	Lawrence Livermore National Laboratory	mcnab1@llnl.gov	
Partners	Joint Industry Project (a consortium consisting of British Petroleum, Statoil, and Sonatrach)			
Stage of Development				
_X_ Fundamental R&D	__ Applied	__ Proof of Concept	__Prototype Testing	__ Demonstration

Technical Background:

The In Salah Project (ISP), a joint venture of BP, Statoil, and Sonatrach, entails a carbon dioxide (CO_2) sequestration effort that has injected millions of tons of CO_2 into a deep saline formation close to a producing gas field in Algeria. At this and other similar sites, CO_2 is injected into a porous, permeable formation that is overlain by an impermeable caprock. Such operations may cause increased pore pressures, leading to potentially large-scale reservoir deformation and possibly altering (or creating) CO_2 migration pathways.

The project provides an opportunity to study key physical and chemical processes in operational deployment of geological carbon sequestration. The proposed research will augment and advance the In Salah Project's earlier in-house reservoir simulation work by adding an explicit account of permeability evolution due to injection-triggered geomechanical and geochemical processes, which together may lead to significant modification—enhancement or degradation—of reservoir, caprock, and wellbore integrity.

Economic implications of possible project findings are potentially significant: identification of consequential CO_2 leakage from the reservoir, or, conversely, a definitive finding that the injected CO_2 is fully contained (i.e., caprock and wellbore integrity is demonstrated), will directly affect decisions concerning monitoring strategies and/or technical risk mitigation approaches, with appreciable financial consequences for the CO_2 injection effort. Premature breakthrough of the CO_2 at one of the producers represents another source of fiscal impact. Operationally, this might require shutting in one or more injectors or producers, potentially reducing the effective productivity of the gas reservoir, leading to financial losses from gas production operations. However, because of the wide range of possible findings, it is difficult to quantify these financial consequences *a priori*.

Relationship to Program:

This project will advance knowledge of the behavior of injected CO_2 within the simulation and risk assessment pathway of the NETL Carbon Sequestration Program. ISP will apply Lawrence Livermore National Laboratory (LLNL) techniques to gain new insights into the behavior of injected CO_2 using LLNL's models to reproduce the observed response to injection. This process will include identifying potential leakage paths through the caprock (e.g., fractures, faults, and wellbores).

The In Salah Project team and LLNL will share data and results to achieve the objectives of the proposed work. The work performed will also benefit the broader community by providing additional information relevant to the creation of geological sequestration standards. This research will exercise and provide further validation of DOE capabilities for predicting the performance of CO_2 storage scenarios.

Primary Project Goal:
The In Salah Project has two fundamental goals:

1. Produce 9 billion cubic feet per year (bcfy) of natural gas from eight fields in the Algerian Central Sahara for 25–30 years.
2. Minimize the associated environmental footprint by capture and subsurface isolation of the excess CO_2 extracted from production streams and subsurface isolation in the Krechba Sandstone reservoir.

Objectives:
This work addresses two fundamental challenges to successful geologic CO_2 isolation at In Salah that are equally relevant to the broad range of CO_2 storage scenarios:

1. Quantify CO_2 plume migration and sequestration partitioning among distinct trapping mechanisms within dynamic, complex permeability fields characterized by multiscale heterogeneity—emphasizing assessment of coupled processes that may lead to early CO_2 breakthrough at production wells.
2. Evaluate geomechanical response and potential supra-reservoir leakage through faults, fractures, and wellbores, which may ultimately reach the surface. Successfully addressing these challenges requires quantitatively representing injection-triggered hydraulic, geochemical, and mechanical processes within reservoir, caprock, and wellbore environments. Such representation requires modeling approaches that explicitly integrate these processes.

It is worth noting that the original statement of work has been essentially unchanged throughout the project because the evolving emphasis of the In Salah Project has mirrored the progression outlined in the original proposal. The project team sought to meet the stated objectives by following a progression of increasing scale and coupled processes. This progression has proven to be an excellent fit for the evolution of data availability from the In Salah site.

10: FWP-FEW-0174 Task 2

Project Number FWP-FEW-0174 Task 2	**Project Title** Fresh Water Generation from Saline Formation-Pressured Carbon Storage				
Contacts DOE/NETL Project Mgr.	**Name** Traci Rodosta	**Organization** NETL – Carbon Sequestration Division	**Email** Traci.Rodosta @netl.doe.gov		
Principal Investigator	Roger Aines	Lawrence Livermore National Laboratory	aines1@ llnl.gov		
Partners	Perlorica, Inc., Rough and Ready, California.				
Stage of Development					
__ Fundamental	__ Applied	X Proof of Concept	_Prototype Testing		__ Demonstration

Technical Background:

This project establishes the potential for using brine pressurized by carbon capture and storage (CCS) operations in saline formations as the feedstock for desalination and water treatment technologies, including reverse osmosis (RO) and nanofiltration (NF). The aquifer pressure resulting from the energy required to inject the carbon dioxide (CO_2) provides all or part of the inlet pressure for the desalination system. Residual brine is reinjected into the formation at net volume reduction, such that the volume of freshwater extracted balances the volume of CO_2 injected into the formation. This process provides additional CO_2 storage capacity in the aquifer, reduces operational risks (e.g., caprock fracturing, contamination of neighboring freshwater aquifers, and seismicity) by relieving overpressure in the formation, and provides a source of low-cost freshwater to offset costs or operational water needs.

The reservoir-pressurized process described here takes advantage of the pressurization of the field caused by CO_2 injection to drive desalination using RO. Thus, costs for freshwater production by this method are expected to be significantly lower than for conventional seawater RO, for which energy costs can be 50% or more of total cost. Plant design for seawater processing is dominated by that energy cost, since water is taken into the plant at low pressure and residual brine must be discharged at low pressure. This process dictates that as much freshwater as possible be extracted from a given volume of seawater, and drives process design toward multiple, sequential RO trains (in which residual brine is taken to sequentially higher pressure) to maximize energy efficiency. In the case of saline formation water where the inlet reservoir is already at high pressure and the residual brine will be returned to the reservoir at high pressure, the amount of freshwater extracted from the brine (% recovered) is no longer a critical parameter, make it feasible to use much simpler, single RO train systems. This simplification results in both cost savings and flexibility in plant design. That flexibility has only been summarily examined in this report and will be an important focus of next year's work. Processing saline formation brines also leads to some increased costs for the treatment plant, primarily the need for pressure-rated piping for the inlet and outlet systems and heat exchangers (because the brine is expected to be produced at temperatures above the working temperature range of RO membranes).

The major project accomplishments and conclusions to date include the following:

1. Many saline formation waters are amenable to conventional RO treatment, such as sodium (Na)-chloride (Cl) brine from the Nugget Formation at the Big Sky Carbon Sequestration Partnership site in Sublette County, Wyoming., which the project team has looked at in this study. At this site, 7.5%–24% brine removal with conventional RO is realistic; higher removal appears achievable with NF. However, Na-Cl-sulfate (SO_4) brine from the underlying Tensleep Formation, which is lower in total dissolved solids (TDS), would support more than 80% removal with conventional RO.
2. Brines from other proposed sequestration sites can now be readily analyzed. An accurate osmotic pressure curve appropriate to these brines can be used to evaluate cost and equipment specifications. Next year the project team will consider more of the U.S. Carbon Sequestration Project site brines as analyses from Phase 3 operations become available.
3. The project team has examined a range of saline formation water compositions relevant or potentially relevant to CCS and noted the principal compositional trends pertinent to evaluating the feasibility of freshwater extraction. They have proposed a general categorization for the feasibility of the process-based TDS.
4. The cost of RO treatment of 10,000–85,000 TDS brines may be half that of conventional seawater plants. An innovative parallel low-recovery approach is proposed for saline formation waters in the upper part of this TDS range.
5. Withdrawing pressurized brine can have very beneficial effects on reservoir pressure, helping to avoid leakage and undesirable geomechanical effects while increasing total available storage capacity.

Relationship to Program:

This project will contribute important freshwater production and reservoir pressure management advances within the CO_2 use/reuse pathway of the NETL Carbon Sequestration Program. The benefits that this project can offer in these two areas are further discussed below.

FRESHWATER PRODUCTION

A typical 1 gigawatt (GW) coal plant emits more than 7 million tons of CO_2 per year. A well-designed capture system might provide 6 million tons for sequestration. Sequestered at a depth of 10,000 ft, this CO_2 would displace about 7.5 million cubic meters of water, or a little less than six million gallons per day. Reverse osmosis treatment of that brine would produce about 6,000 acre-feet of freshwater, which could serve the needs of 10,000 homes, irrigate 2,000 acres of cropland, or provide half of the total freshwater usage of a typical 1 GW integrated gasification combined cycle power plant. A goal of this project is to establish the cost of providing this water. The project team's initial results indicate that the cost would be about half the cost of seawater reverse osmosis. This is a co-benefit of the cost of pressurizing the CO_2 for injection.

RESERVOIR PRESSURE MANAGEMENT

Many decisions regarding safety and storage volume in brine reservoirs are dependent on remaining below certain critical pressures that can cause effects like fracturing. Producing brine and reducing its volume by making freshwater (and returning the concentrated brine to the reservoir) makes pressure management available to the reservoir operator, potentially greatly increasing their range of operation by permitting more volume to be accessed at appropriate pressures.

Primary Project Goal:
This project is establishing the potential for using brine pressurized by CCS operations in saline formations as the feedstock for desalination and water treatment technologies including RO and NF.

Objectives:

1. Identify which brines in currently planned sequestration efforts may be appropriate for this process and determine their chemistry differences compared to conventional seawater RO through modeling of the RO process, particularly osmotic pressure during treatment.
2. Identify chemical and treatment process steps required (e.g., NF) by identifying brines that cannot be treated by simple one-step RO and characterizing the additional chemical moieties present.
3. Estimate process costs using the conceptual treatment model used by the current RO industry for planning treatment processes.
4. Test treatment strategies on a laboratory scale; evaluate scaling and precipitation control strategies.
5. Analyze process costs using a detailed treatment model that takes into account the additional chemical controls required for aquifer brines and provides a detailed analysis of the additional energy and operations needs of this process.
6. Establish requirements for field demonstration through discussing technical results with DOE and U.S. partnerships to establish key parameters necessary for demonstration.

11: DE-NT0004730

Project Number DE-NT0004730	**Project Title** Carbon Sequestration Monitoring Activities			
Contacts DOE/NETL Project Mgr.	**Name** William Aljoe	**Organization** NETL – Carbon Sequestration Division	**Email** william.aljoe@netl.doe.gov	
Principal Investigator	Carol D. Frost	University of Wyoming	frost@uwyo.edu	
Partners	Wyoming State Geological Survey			
Stage of Development				
__ Fundamental	__ Applied	__ Proof of Concept	__ Prototype Testing	X Demonstration

Technical Background:

In its "Carbon Sequestration Technology Roadmap and Program Plan 2007," NETL identifies a major programmatic objective to conduct extended field tests to characterize fully potential carbon dioxide (CO_2) storage sites and to demonstrate the long-term storage of sequestered carbon. Among the challenges in this area are the "improved understanding of CO_2 flow and trapping within the reservoir and the development and deployment of technologies such as simulation models and monitoring systems". Paleozoic deep-saline aquifers in southwestern Wyoming are the most promising targets for geologic CO_2 sequestration in Wyoming, and are possibly the most promising sequestration sites in the Rocky Mountain region.

One of these deep saline aquifers—the Moxa Arch—is a 120 mi long north-south trending anticline that plunges beneath the Wyoming Thrust Belt on the north and is bounded on the south by the Uinta Mountains. Several oil and gas fields along the Moxa Arch contain accumulations of natural CO_2. The largest of these is the La Barge Platform, which encompasses approximately 800 sq mi.

The University of Wyoming (UW) identified Moxa Arch as a promising site for a commercial-scale sequestration for a number of reasons:

1. It is a geological structure that has stored CO_2 for many millions of years.
2. Several formations appear to be suitable sequestration reservoirs.
3. CO_2 is presently being produced and sold for enhanced oil recovery in this area, and more CO_2 is potentially available for this and other uses, including for a future sequestration demonstration.

Several formations may be suitable for storage of impure CO_2 gas, foremost among them the Madison Limestone, Bighorn Dolomite, and Nugget Sandstone. These storage units are overlain by a series of sealing lithologies that serve as regional hydrocarbon, CO_2, and helium (He) seals, thus ensuring fluid containment.

Another reason that Moxa Arch was identified as a good target site for sequestration is that ExxonMobil has been producing natural gas on the La Barge Platform from Madison Limestone, which contains CO_2, He, methane (CH_4), nitrogen (N), and hydrogen sulfide (H_2S). The presence of these gases trapped in this structure indicates its promise for sequestration. In fact, the area is already used for this purpose; in 2005, ExxonMobil began sequestering a portion of the

CO_2 and all the H_2S separated at its Shute Creek gas plant, 40 mi south of the producing field. To date, two injection wells have sequestered over 2 million tons of CO_2 in the Madison's water leg below 18,000 ft.

There are 11 identified tasks that comprise this project. A detailed description of the tasks and subtasks is as follows:

TASK 1.0—PROJECT MANAGEMENT AND PLANNING

This task serves as oversight for the other 10 tasks described in the plan of work and directs outreach activities for the dissemination of research findings to agencies, industry, and citizens. Under this task, principal researchers and their collaborators for the individual project tasks hold meetings each quarter to share preliminary results, assess progress, and discuss questions or problems. A final workshop for researchers and representatives from state and federal agencies, industry, and the public will be held to share results with the wider community and to discuss the broader implications of the findings for regulatory or policy issues.

This task will also design and create the framework of an interdisciplinary, project-specific, carbon cyberinfrastructure to support collaborative CO_2 sequestration research among UW scientists and their collaborators. Specifically, the project will establish a custom science information infrastructure, integrating research results to support the assessment of best injection sites and gas resources; the construction of sequestration performance models; and the design of a measurement, monitoring, and verification (MMV) program for future sequestration activities in the state and region.

TASK 2.0—GEOLOGICAL CHARACTERIZATION: ASSEMBLING AND VALIDATING A WELL DATABASE

Large-scale sequestration of CO_2 in geologic reservoirs requires development of procedures and protocols to ensure that siting of injection and monitoring wells is accurate and that site risk assessment is robust. A sound preinjection geologic model of the potential injection site requires data from preexisting hydrocarbon wells. As part of characterization efforts, UW will assemble and validate a database that includes information about existing well locations in that portion of the Moxa Arch identified by the project personnel and their collaborators and partners at their initial meeting. This data is an essential part of site characterization because wells have the potential to act as conduits for leaks of CO_2 from the target reservoir. UW will generate a well database and a GIS system that are consistent with emerging standards and conventions for CCS system analysis.

TASK 3.0—GEOLOGICAL CHARACTERIZATION: GEOCHEMICAL CHARACTERIZATION OF PRODUCED WATERS AND GASES

In this task, UW will compile and generate preliminary geochemical data on the natural geochemical variation in the water and gases of the Nugget Sandstone and the Madison Limestone and overlying formations in the Moxa Arch. UW will collect a suite of produced water and gas samples from operational oil- and gas-producing wells established in Nugget Sandstone and Madison Limestone and other overlying formations and analyze them for stable isotopic and major ion chemical compositions.

TASK 4.0—GEOLOGIC CHARACTERIZATION: SUBSURFACE STRUCTURAL EVALUATION

The three-dimensional model generated by this work will also provide data necessary for the complete and accurate flow modeling of CO_2 in the reservoirs. Some uncertainty will exist in the subsurface structural interpretation that can be resolved only through drilling, injection tests, and well monitoring; however, a subsurface model will provide the necessary foundation for the best possible reservoir characterization. In this task, UW will focus on the subsurface structure of the La Barge Platform through an analysis of seismic and well log data to create a three dimensional subsurface model. This will provide critical information about the shape and volume of potential targeted reservoirs, fault locations and offsets, and other information.

TASK 5.0—GEOLOGIC CHARACTERIZATION: SURFACE STRUCTURAL ANALYSIS

This task involves a multiscale evaluation of the surface structural geology of the La Barge Platform. It will provide critical information on regional and local fracture and fault systems through the preparation of serial cross sections and outcrop-scale analyses of fracture arrays and populations of small-scale faults. Laboratory studies on fault rocks and mineralized fractures will provide important information on deformation mechanisms and fluid composition that have affected the stratigraphic units targeted for carbon sequestration.

TASK 6.0—LABORATORY EXPERIMENTAL ACTIVITIES: MIXED-PHASE (CO_2+H_2O) FLUID-ROCK REACTIONS

UW will experimentally evaluate mixed-phase fluid rock reactions and processes within the Nugget Sandstone and its caprock, the Twin Creek Limestone, using rocking autoclaves and stirred reactors. Supercritical CO_2 will be introduced into ongoing reactions to evaluate CO_2 trapping mechanisms and interactions with actual aquifer rocks and caprocks while in situ fluid-gas sampling will gauge reaction progress. In addition to developing MMV protocols, results from these batch experiments will be used to constrain computational models and design future, more complicated dynamic core-flood experiments that will account for hydrodynamic flow. CO_2-N_2 mixtures will be used to regulate CO_2 fugacity, reserving reactive, toxic, and flammable CO_2-H_2S-CH_4 mixtures for future experiments.

TASK 7.0—LABORATORY EXPERIMENTAL ACTIVITIES: CO_2/BRINE RELATIVE PERMEABILITIES

Accurate, appropriately scaled relative permeabilities are important for determining the storage capacity and fate of sequestrated CO_2. In this task, UW will measure relative permeabilities, hysteresis, and capillary trapping of CO_2. To carry out the experiments through aquifer core samples, UW will employ a recently established, state-of-the-art, multiphase flow laboratory that benefits from a medical CT scanner that can be used to measure in situ saturation during core-flood experiments. These results are important to developing and validating models that are capable of predicting fluid flow behavior and properties. Utilizing the physically based flow properties can significantly reduce the uncertainties associated with estimations of storage capacity in geological formations and predictions of the fate of sequestrated CO_2.

TASK 8.0—MODELING ACTIVITIES: FEASIBILITY OF GEOPHYSICAL MODELING OF CO_2 RESERVOIRS

UW will conduct a detailed study on full waveform synthetic computation and inversion for elastic properties and microseismic sources for fracture characterization for the purpose of CO_2 sequestration and monitoring in the Moxa Arch. The study will use known physical properties from relevant Wyoming aquifers; the aquifer water will be fluid substituted with different concentrations of CO_2, and full waveform synthetic seismograms will be computed. Inverting these synthetics for elastic properties will then allow the project team to compile the sensitivity levels of the inversion to various levels of CO_2 saturation and volume. A complementary aspect of our work will be to simulate the microseismic responses from simulated injection rates, which will be accomplished by inverting the computed waveforms for source signatures to characterize the space-time fracture evolution.

TASK 9.0—MODELING ACTIVITIES: MULTISCALE MODELING AND NUMERICAL SIMULATION OF CO_2 INJECTION

This task focuses on the development of an open-source, noncommercial computer model to quantify the uncertainties associated with CO_2 sequestration in the deep geologic formations of the Moxa Arch. This open-source code will be amenable to implementation on high-performance computers. The simulation code to be developed in this proposal will aid the assessment and monitoring of the Moxa Arch CO_2 sequestration project by providing accurate predictions of the migration and trapping of the CO_2 plume. The resulting simulator will have unique capabilities to handle the strongly nonlinear physics and chemistry of the CO_2/brine flow and its interaction with multiscale geological heterogeneities.

TASK 10.0—MODELING ACTIVITIES: DETERMINATION OF OPTIMAL GEOLOGIC MODEL COMPLEXITY

Two geological formations at the Moxa Arch will be evaluated for impure CO_2 injection. In this task, a numerical scoping analysis will evaluate an optimal geological model complexity necessary to capture both the prediction envelope and sensitivity of a detailed Earth model. For each formation, a suite of models of decreasing complexity will be built, each incorporating multiple parameter uncertainties specific to the La Barge field. An efficient sensitivity analysis will be conducted for each model to identify a full range of best-to-worst scenarios and factor(s) exerting first-order impact on flow of the mixed gases, their storage, and leakage. By comparing both model prediction and sensitivity, an optimal level of geological model complexity will be determined.

TASK 11.0—PERFORMANCE ASSESSMENT

The Wyoming State Geological Survey will incorporate the geological, geophysical, and petrophysical data derived in Tasks 2–10 into a three-dimensional Earthvision model (i.e., Dynamic Graphics Spatial Modeling software) of an area with a 10 mi radius of the proposed CO_2 injection site. This model will initially be used to extract one-dimensional well profiles and two-dimensional cross sections in order to approximate CO_2 injection and flow in the subsurface. Extensive collaboration with other project investigators will be necessary to capture all essential details of the hydrostratigraphy of the target formations (Tensleep, Madison, Bighorn), as will including strata above and below these formations and any significant faults within the targeted rock volume. Next, a probability-based performance assessment model utilizing the one- and two-dimensional grids extracted from the hydrostratigraphic/flow models will be developed within the GoldSim, FEHM, and CO_2–PENS software packages. The goal of the performance assessment model of subsurface CO_2 flow will provide first approximations of the probability of such things as leakage rates, likely storage capacity, and impacts on accessible environments.

Relationship to Program:

This project will advance the knowledge of a potential CO_2 sequestration site, within the monitoring, verification, and accounting pathway of the NETL Carbon Sequestration Program.

- Provide an improved understanding of the injectivity, capacity, and storability of regionally significant formation(s) necessary for a future carbon sequestration test on the Moxa Arch
- Provide the data and modeling necessary to create a carbon sequestration demonstration project in Wyoming

Primary Project Goal:

The goal of this project is to develop the background information and procedures necessary to prepare for geologic CO_2 sequestration in the Moxa Arch, via research in the following priority areas:

1. Geologic characterization
2. Laboratory experimental activities
3. Modeling
4. Construction of a preliminary performance assessment model

Objectives:

PRIORITY AREA A (GEOLOGICAL CHARACTERIZATION)

The objective is the creation of a three-dimensional geological model of the potential injection site that includes thicknesses of target formations, locations and displacements of faults and fractures, the baseline geochemical and isotopic composition of the target aquifers, and locations and completion details of existing wells. These results will inform the performance assessment model (Priority Area D). Specific products by which success will be judged will include an electronic well database, a geochemical and isotopic produced water database, a multiscale fault and fracture analysis, a series of regional cross sections, and a three-dimensional subsurface structure model.

PRIORITY AREA B (EXPERIMENTAL LABORATORY ACTIVITIES)

The objective is to identify flow properties and fluid-rock reactions that will occur during CO_2 injection into the target aquifer. Specific products will include description and computational models of major geochemical reactions, measurement of CO_2/brine relative permeabilities, and high-resolution three-dimensional images of reservoir rock and pore networks at the core scale. This information also will be contributed to the development of the preliminary Performance Assessment (Priority D).

PRIORITY AREA C (MODELING)

The objective is to determine the most appropriate seismic monitoring program and modeling strategies for monitoring this site, thereby preparing for a future CO_2 sequestration project. This objective will be met by accomplishing the following:

1. Evaluate the feasibility of geophysical modeling of CO_2 reservoirs using both active and passive seismic methods.
2. Use modeling and numerical simulation to quantify the uncertainties associated with CO_2 sequestration in the deep geologic formations of the Moxa Arch.
3. Determine the necessary optimal geological model complexity.

PRIORITY AREA D (CONSTRUCTION OF A PRELIMINARY PERFORMANCE ASSESSMENT MODEL)

The objective is to create a model that will delineate the site in terms of suitable reservoirs for carbon storage, the capacity of target formations for CO_2 sequestration, the integrity of the caprock, projections of plume migration and brine displacement, and potential for leakage either along faults and fractures and/or existing wells. Successful completion of the performance assessment model is a prerequisite to a future CO_2-injection demonstration project.

12: DE-FC26-04NT42262

Project Number	**Project Title**			
DE-FC26-04NT42262	Basic Science of Retention Issues, Risk Assessment & Measurement, Monitoring, & Verification for Geologic CO_2 Sequestration (ZERT)			
Contacts	**Name**	**Organization**	**Email**	
DOE/NETL Project Mgr.	William W. Aljoe	NETL – Carbon Sequestration Division	william.aljoe@netl.doe.gov	
Principal Investigator	Lee H. Spangler	Montana State University	spangler@montana.edu	
Partners	Los Alamos National Laboratory Lawrence Berkeley National Laboratory Lawrence Livermore National Laboratory Pacific Northwest National Laboratory National Energy Technology Laboratory West Virginia University			
Stage of Development				
_X_ Fundamental R&D	__Applied R&D	_ Proof of Concept	_ Prototype Testing	_ Demonstration

Technical Background:

The existence of naturally occurring carbon dioxide (CO_2) reservoirs and experience with enhanced oil recovery operations are strong indicators that engineered subsurface storage of CO_2 can be safe and effective. However, large-scale deployment will require greater confidence in understanding the fate of the CO_2 in the subsurface for both economic and safety reasons. The participating institutions in the Zero Emissions Research and Technology (ZERT) Collaborative have expertise in the development of code to simulate multiphase flow through porous media and fracture networks; facilities and expertise for measurement of fundamental physical and chemical properties of systems under appropriate temperature and pressure conditions; and expertise in measurement, monitoring, and verification. This project focuses on the basic science and development needs for improving the state of knowledge of CO_2 behavior in the subsurface by assessing knowledge gaps in fundamental physical and chemical properties in relevant systems; making measurements of those properties; improving numerical models by improving parameterization using these studies and extending code capability; and testing efficacy and detection limits of measurement, monitoring, and verification techniques. This information and the improved techniques can be incorporated into a systems-level model for risk assessment, which is also being developed in this project.

The project includes the following major areas of study:

1. IMPROVEMENT OF COMPUTATIONAL TOOLS

The goal of this effort is to develop reliable techniques to predict CO_2 migration and trapping mechanisms. The computer simulators TOUGH2 (Transport Of Unsaturated Groundwater and Heat) and TOUGHREACT are being enhanced to improve the simulation of the fate and transport of CO_2 in the subsurface, and are being applied to investigate migration and trapping processes. For modeling CO_2 injection and migration, the project team is developing ECO2N (i.e., an equation-of-state module for water, salt, and CO_2 in saline formation storage), which includes a parallel version for very large problems. For improved modeling of mineral trapping, the project team is developing TOUGHREACT, which is being expanded to include reactive geochemistry, and developing capabilities for modeling hysteresis in relative permeability and capillary pressure. These TOUGH2 codes are available to the public through the DOE's Energy Science and Technology Software Center.

2. MEASUREMENT AND MONITORING TECHNIQUES TO VERIFY STORAGE AND TRACK MIGRATION OF CO_2.

The goal of this effort is to develop reliable techniques to demonstrate storage effectiveness, and to quantify migration out of the storage formation and release rates at the surface. A combination of surface and subsurface approaches are being developed for verifying storage effectiveness, some of which are being tested at natural analog sites. Additionally, the project team has developed a control site on Montana State University property with the following goals:

- Develop a site with known injection rates for testing near surface monitoring techniques.
- Use this site to establish detection limits for monitoring technologies.
- Use this site to improve models for groundwater – vadose zone – atmospheric dispersion models.
- Develop a site that is accessible and available for multiple seasons/years.

3. DEVELOPMENT OF A COMPREHENSIVE PERFORMANCE AND RISK ASSESSMENT FRAMEWORK.

The goal of this effort is to develop systems-level models on which a decision can be based with the ability to flexibly link to a wide variety of detailed physical and chemical process information/models.

4. FUNDAMENTAL GEOPHYSICAL, GEOCHEMICAL, AND HYDROLOGICAL INVESTIGATIONS OF CO_2 STORAGE

The goal of this effort is to develop understanding and confidence in solubility trapping, residual gas trapping, and mineral trapping, and to identify new trapping mechanisms that can contribute to greater storage security.

5. INVESTIGATION OF INNOVATIVE BIO-BASED MITIGATION STRATEGIES

The goal of this effort is to evaluate the potential for microbial biofilms as a technology that can mitigate CO_2 leakage from geologic storage sites. The working concept is that biofilms and other deposits can be formed so as to plug preferential flow pathways near CO_2 injection or monitoring wells, thereby reducing the potential for unwanted upward migration of stored CO_2.The first major accomplishment was the develop of a novel core testing system, which is capable of growing microbial biofilms in one-inch diameter rock cores at pressures up to 2,500 pound-force per square inch gauge (psig) and temperatures of up to 50°C.

Relationship to Program:

This project will support advances within the monitoring, verification, and accounting pathway of the NETL Carbon Sequestration Program. Fundamental physical and chemical properties are being measured that will improve parameterization and accuracy of simulation models. Near-surface detection suites are being tested in a controlled fashion, which should provide useful information to sequestration project measurement, monitoring, and verification design. Additionally, new measurement, monitoring, and verification techniques are being developed, and the ZERT field site can serve as a test bed for new technologies. Finally, multiple simulation codes are being improved in a wide variety of ways under this project. These improved codes are already being applied to other projects (including multiple Phase II and III partnership projects).

Primary Project Goal:

The primary project goal is to perform basic science and technology development to fill critical needs of the Carbon Sequestration Program, specifically in the areas of measurement, monitoring, and verification; computational techniques improvements; risk assessment and mitigation; and fundamental geoscience studies of CO_2 properties and behavior.

Objectives:

The major objectives of the project include the following:

1. Improve computational tools for simulation of CO_2 behavior in the subsurface. This includes the addition of reactive transport, the development of coupled models to include geomechanics, and the inclusion of hysteretic effects and parallelization.
2. Test the efficacy of near-surface detection techniques, help establish detection limits for those techniques, and provide data to assist in development of transport models in the near-surface region. The development of a field site will help to help accomplish this objective.
3. Develop a comprehensive risk assessment framework that will allow flexible coupling of multiple computational models for different components/processes of the system.
4. Perform gap analysis to identify critical missing data for CO_2 properties in the subsurface, including thermodynamic properties of CO_2-brine mixtures, reaction rates, relative permeabilities, and conduct laboratory-based experiments to generate the critical data.
5. Investigate innovative bio-based mitigation strategies.

13: FWP-AACH-139

Project Number FWP-AACH-139	Project Title New Approach for Long Term Monitoring of Leaks from Geological Sequestration			
Contacts DOE/NETL Project Mgr.	**Name** Joshua Hull	**Organization** NETL – Carbon Sequestration Division	**Email** Joshua.Hull@ netl.doe.gov	
Principal Investigator	Lucian Wielopolski	Brookhaven National Laboratory	lwielo@bnl.gov	
Partners				
Stage of Development				
_Fundamental	__ Applied R&D	X Proof of Concept	_Prototype Testing	__ Demonstration

Technical Background:

The state-of-the-art of soil carbon analysis is a chemical method based on dry combustion (DC) of small samples collected in the field. Incremental improvements over several decades entrenched DC as the leading method of choice. However, the increasing demand for soil analyses and the disadvantages of needing to collect soil samples, combined with the inherent limitations of the DC method, spurred the development of new technologies. The novel approach to in situ analysis of soil carbon offered by Inelastic Neutron Scattering (INS) rests on sound physical principles of gamma ray spectroscopy induced by the nuclear interactions of fast neutrons with soil elements. INS uniquely affords nondestructive in situ analysis of large soil volumes, operating in both static and scanning modes, and provides multi-elemental analysis, promptly rendering the results at the end of the data-acquisition period. The INS system overcomes many of DC's shortcomings while revolutionizing the current spatial and temporal soil-sampling paradigms by greatly reducing the effort needed and the costs entailed in soil analysis.

Relationship to Program:

This project contributes important advances in sampling and analysis to the monitoring, verification, and accounting pathway of the NETL Carbon Sequestration Program by deploying a new, advanced technology for soil carbon analysis that would revolutionize the current paradigms of soil sampling and analysis. The INS system will play a pivotal role in numerous projects and programs that require soil carbon analysis. The project is critically important to several DOE programs and plays a direct role in NETL's Clean Coal program. Examples of project benefits and contributions include the following:

1. Recognizing the vast coal reserves in the United States and their contribution to greenhouse gas (GHG) emissions, the NETL embarked on a Clean Coal program, which focuses on the cleaner use of coal and the capture and storage of CO_2 emissions in deep geological formations, and a Carbon Capture and Storage (CCS) program, which directs extensive effort toward identifying and understanding the factors influencing the permanence of CO_2 storage on human—and ecosystem—safety. Successful demonstration of the INS system for long-term monitoring of small CO_2 leaks will benefit NETL tremendously.
2. INS will contribute directly to DOE's Terrestrial Carbon Processes program and the U.S. Global Climate Change Research Program. The project also supports the DOE mission Protect Our Living Planet.
3. Because of the INS's unique characteristics, it will support research that was not previously possible.

4. The INS will provide an independent, improved assessment of the global carbon stocks needed by climate modelers in accounting for a missing source or sink of the atmospheric carbon.
5. The project will expedite trading with carbon credits and improve the quality of contract verification, thus increasing the value of the contract.
6. A second-generation INS system will offer insight into the unperturbed soil carbon-depth profile (which is not possible at present), addressing the basic question of whether more carbon is being sequestered, or simply redistributed.
7. INS can be adapted for monitoring carbon in wetlands.

Primary Project Goal:

To develop a new nondestructive quantitative technology for monitoring large-scale spatial and temporal changes in the belowground carbon levels affected by soil-management practices and environmental factors, and to provide long-term assurance monitoring of slow CO_2 leakage from deep geological CO_2 reservoirs.

Objectives:

The project goal may be achieved by accomplishing tasks associated with the following objectives:

1. DEPLOYMENT OF A RUGGEDIZED INS SYSTEM

In past years, the project team developed a laboratory system for soil analysis and tested it in the field. However, a rugged system is needed to prevent system failures typical of using an experimentally conceived system under demanding and sometimes harsh field conditions; therefore, the outdoor temperature span over winter and summer caused crystal detectors to drift, requiring digital corrections. A new, ruggedized INS system is based on an autonomous integrated platform wherein all the electronics are mounted beside the detectors, insulated, and interfaced with buckle-head connectors.

2. DEPLOYMENT OF AN INS BETA PROTOTYPE WITH IMPROVED SENSITIVITY

Acceptance tests are in progress of an INS beta prototype system consisting of 16 detectors with proper electronics, rather than the original three. There is an anticipated fivefold increase in sensitivity and an estimated twofold increase in minimum detection limit with this beta prototype that is planned to be deployed at the Zero Emissions Research and Technology Center (ZERT) facility in Montana. No unusual technical obstacles are envisioned; any potential malfunction of the new electronics can be readily repaired with alternative circuitry.

3. CONFIRMATION OF THE INS APPLICABILITY FOR DETECTING CO_2 LEAKS

The results from two previous experiments at the ZERT facility, using the current INS system, strongly suggest that belowground carbon is lost within a month from a fumigation site located above a horizontal CO_2 well. The project team intends to confirm these results for the third time with a fully operational system, and possibly, with the INS beta prototype.

4. IMPLEMENTATION OF ADVANCED SPECTRAL ANALYSIS SOFTWARE FOR IMPROVED PRECISION

Presently, gamma ray spectra are analyzed using a basic trapezoidal algorithm to calculate the net number of counts under the photopeak area that directly is related to carbon concentration in soil. This approach is satisfactory for relatively simple spectra. However, to reduce error propagation and account better for peak interferences from other elements, the project team is implementing an advanced Library Least Squares (LLS) methodology. LLS assert that a measured spectrum is a linear superposition of individual spectra, herein referred to as the library spectra that are determined by least-squares fitting to a measured unknown spectrum. The library spectra are determined experimentally or analytically for every element or an assembly of elements for which the composition remains invariant. The fitted values represent the elemental concentrations in soil.

5. IDENTIFICATION OF THE PROCESSES AFFECTING THE BELOWGROUND CARBON CONTENT IN SOIL IN THE PRESENCE OF CHRONIC LOW LEVEL UNDERGROUND CO_2 SOURCES IN CONTRAST TO ELEVATED ATMOSPHERIC CO_2

The exact processes by which underground CO_2 leaks cause loss of organic carbon in soil are not completely understood, albeit, it is generally recognized that asphyxiation of the plant's roots and their microbial fauna might be the main sources for these losses. Understanding these processes is important for a) assessing the impact of low-level chronic CO_2leakages on the ecosystem, and, b) designing an integrated approach for monitoring slow chronic CO_2 leakages from geological sequestration sites.

6. DELIVERY OF AN INTEGRATED SYSTEM FOR SURFACE MONITORING OF CO_2 LEAKAGE FROM GEOLOGICAL SEQUESTRATION SITES, MONITORING SOIL QUALITY DURING RESTORATION OF ABANDONED MINE LANDS, AND CONTRACT VALIDATION OF TRADING WITH CARBON CREDITS

On a simple mobile platform, the project team will assemble and integrate multiple techniques with demonstrated individual capabilities to measure above and belowground changes due to high CO_2 leak rates. However, the relationship between instrumental minimum detectable limits (MDLs) and CO_2 leak rates must be determined and distinguished from other possible environmental causes inducing similar responses. Using multiple modalities mounted on a single mobile platform will enhance the ability to cross-validate the instruments' responses; further, the areal scanning capability of the integrated system will allow spatial integration of the signal, whereas invoking the monitoring of the biota response would provide a time-integrated response. These two unique features will amplify any low-level signal that might be undetectable by any other means that provide a point measurement in space and time.

Concurrently, the project team will deliver a ruggedized INS system for monitoring carbon in soil in various reclamation schemes for reforesting abandoned mine lands or reclaiming them for growing biofuel stock. In both cases, the data from INS will be essential to expedite trading with carbon credits. Each of the methods and steps taken were demonstrated individually in the laboratory and in field measurements. The systems would need to be ruggedized; however, this does not pose any critical uncertainty. The greatest uncertainty can be ascribed to determination of the level of chronic CO_2 seepage that would induce observable changes in the soil's parameters; such information does not exist. Alternatively, the project team could establish correspondence between the instrumental MDLs and CO_2 leak rates, and quantify these leaks as an upper limit for field monitoring.

14: ORD-GEC.1610251.600.A

Project Number ORD-GEC.1610251.600.A	**Project Title** National Risk Assessment Partnership (NRAP)			
Contacts DOE/NETL Project Mgr.	**Name** Grant Bromhal	**Organization** NETL – Office of Research and Development	**Email** Grant.Bromhal @netl.doe.gov	
Principal Investigator	Grant Bromhal	NETL – Office of Research and Development	Grant.Bromhal @netl.doe.gov	
Partners	Los Alamos National Laboratory Lawrence Berkeley National Laboratory Lawrence Livermore National Laboratory Pacific Northwest National Laboratory			
Stage of Development				
__ Fundamental	__ Applied	X Proof of Concept	__ Prototype Testing	__Demonstration

Technical Background:

The deployment of carbon sequestration at a significant scale requires an efficient but comprehensive scientific approach for assessing the short- and long-term performance of natural geologic systems that span a range of geologic environments. Carbon dioxide (CO_2) storage operations may utilize deeper saline formations and require prediction of the post-operations behavior of coupled engineered and natural systems, necessitating the prediction of CO_2 movement/reactivity over large areas and long periods of time. A range of field-scale efforts suggest that geologic sites can be successfully exploited to retain large volumes of injected CO_2. A robust, science-based risk assessment approach will help ensure the success of large-scale projects and guarantee that any potential uncertainties at a given site are well understood in order to produce optimal data collection and monitoring.

The U.S. Department of Energy's Carbon Sequestration Program is developing key tools and science to accelerate and enable large-scale storage of CO_2. The program ranges from fundamental reactions between fluids and rocks to the development of new frameworks for multiscale predictions of the behavior of engineered-natural systems. As these programs become more mature, as more is understood about geologic carbon storage (GCS), and as stakeholders in the process learn more about the benefits and potential ramifications of GCS, it has become widely recognized that the ability to comprehensively assess key risks in the carbon storage system is critical to full deployment of GCS technology. To this end, the Sequestration Program has supported a number of investigator-level efforts to address various aspects of risk, and the Regional Partnership program is applying this knowledge to its field demonstrations. The National Risk Assessment Partnership (NRAP) was recently initiated within the Sequestration program function as a national resource to facilitate integration of the wide range of risk knowledge being developed; to ensure comprehensiveness by assessing key gaps that remain to be addressed and developing and implementing plans to address these gaps; and to leverage the breadth of risk-related expertise across the DOE complex to ensure the science base for the assessment of long-term risks for carbon capture and storage (CCS). As such, NRAP is a collaboration among multiple national laboratories, including Los Alamos National Laboratory, Lawrence

Berkeley National Laboratory, Lawrence Livermore National Laboratory, National Energy Technology Laboratory (project lead), and Pacific Northwest National Laboratory.

To identify key technical needs and to ensure science is focused on addressing these needs, it is necessary to facilitate ongoing discussions between key stakeholders, including national and state regulators, operators, and insurers.

Additionally, there is much work being done in basic sciences related to processes important to carbon sequestration. However, it is necessary to bridge the gap between ongoing programs in the basic sciences, such as the Energy Frontier Research Centers, and the applications for these programs.

Relationship to Program:

This project contributes important advances in risk assessment tools and practices to the simulation and risk assessment pathway of NETL's Carbon Sequestration Program. The project benefits to the program include the following:

- Better science-based information to decision makers for making go/no-go decisions about selecting sequestration sites, methods to reduce risks during operation, and proposed mitigation options
- Bridge between basic science and the application of risk assessment to sequestration
- Tools for performing quantitative (probabilistic) risk assessment for sequestration sites
- Best practices for risk assessment of sequestration sites and input to best practices for monitoring and site characterization

Primary Project Goal:

The primary goal of the project is to provide the scientific underpinning for risk assessment to DOE-Office of Fossil Energy (FE) with respect to long-term storage of CO_2, including the assessment of residual risk associated with a site post-closure, through the following tasks:

1. Providing a link between DOE-FE and DOE-Office of Science
2. Identifying scientific gaps in the program related to risk assessment and helping DOE determine how these gaps should be filled
3. Performing research to fill gaps in the science base for risk assessment, where appropriate

Objectives:

A primary goal of NRAP is to help identify gaps in the current science base for risk assessment of long-term geologic storage and to help bridge those gaps.

To this end, NRAP objectives include the following:

1. Initiate a process to identify critical gaps in six different areas related to sequestration: wellbore integrity, natural seal integrity, protection of groundwater (and other subsurface resources), geomechanical performance, strategic monitoring, and systems modeling.
2. Develop an initial research plan to address key needs in risk assessment that coordinates activities across these national laboratories and promotes strategic collaborations on activities.
3. Initiate research needed to fill gaps in the science base for risk assessment.

4. NRAP has begun to develop collaborations beyond the five-national-laboratories group, serving as a base to integrate strengths from universities and identify synergies with other research entities.
5. The types of deliverables that will be produced include the following:
6. Validated quantitative (probabilistic) risk-assessment and hazard/risk-management methodologies for field sites
7. Technical/scientific basis for best practices and standards for risk assessment for broad deployment of CCS in 2020
8. Scientific basis of a framework for quantitative assessment of risk associated with long-term stewardship
9. Key technical findings around fundamental processes and risk elements
10. A common platform and data set(s) to share with the scientific community

15: OSAP-CO2-EOR LCA

Project Number OSAP-CO2-EOR LCA	**Project Title** Assessing Net Storage Potential of CO2-Flood Enhanced Oil Recovery: A Life Cycle Analysis Perspective			
Contacts DOE/NETL Project Mgr.	**Name** Tim Skone	**Organization** NETL – Office of Systems, Analysis, and Planning	**Email** Timothy.Skone@netl.doe.gov	
Principal Investigator	Robert Dilmore	NETL – Office of Systems, Analysis, and Planning	dilmore@netl.doe.gov	
Partners				
Stage of Development				
__ Fundamental	_X_ Applied R&D	__ Proof of Concept	__ Prototype Testing	__Demonstration

Technical Background:

Carbon dioxide flood-enhanced oil recovery (CO_2-EOR) is an established technology that stimulates incremental oil production in fields depleted through primary and secondary water flood recovery operations. Studies published by DOE suggest that the domestic potential for CO_2-EOR could be as high as 119 billion barrels of additional technically recoverable oil. At present, the application of CO_2-EOR is limited by the availability of CO_2, with 70% of CO_2 used in EOR operations coming from natural sources and 30% (approximately 20 million metric tons per year) coming from industrial and byproduct sources. Proposed climate change legislation calling for large-scale capture and sequestration of anthropogenic CO_2 would resolve that limitation, while also creating an opportunity to realize large increases in incremental oil production and achieve significant geologic sequestration of CO_2 (as much as 13 gigatons of CO_2 storage capability). There remains, however, some disagreement on the efficiency of CO_2-EOR as a mechanism for storing relatively large volumes of CO_2. Some interests claim that CO_2-EOR has no value for CO_2 sequestration while others claim that the technology can be used to provide “carbon-free” oil.

Relationship to Program:

This project makes important advances in life-cycle emissions assessments of CO_2-EOR technology as part of the storage pathway of NETL’s Carbon Sequestration Program. It supports the sequestration program goals of 90% CO_2 capture with 99% storage permanence by proving detailed characterization of emissions that may be considered to partially offset the benefit of gross CO_2 sequestration. This effort serves to better characterize the net sequestration benefit associated with CO_2-EOR for a set of operational scenarios. Previous evaluations of CO_2-EOR estimate the potential gross sequestration benefit that can be realized through application of this technology but do not take into account the greenhouse gas emissions associated with facility operations. Results of this analysis will provide information to support the argument for the potential of geologic sequestration from CO_2-EOR and will provide insights into operational alternatives that could increase the benefit of net sequestration.

In addition to supporting DOE sequestration program goals, this work also has synergies with and supports efforts of the following:

- The Strategic Center for Natural Gas and Oil effort to evaluate the potential application of CO_2-EOR to enhance the production of domestic energy resources in an environmentally and economically sustainable manner
- U.S. Air Force-sponsored interagency working group effort to develop and demonstrate methodologies to determine life-cycle greenhouse gas emissions associated with transportation fuels in response to requirement defined in the Energy Independence and Security Act of 2007

Primary Project Goal:
The goal of this effort is to contribute to the clarification of the greenhouse gas emissions mitigation performance of CO_2-EOR technology by developing a detailed inventory of associated activities, resource demands, emissions, and products, and by providing insight into likely benefits and drawbacks of selected technology operational scenarios with respect to fossil resource production and greenhouse gas emissions management.

Objectives:
To accomplish the primary project goal, the following four project objectives have been defined:

1. Establish a design basis that considers the study purpose and intended audience, analysis system boundary, technology operational scenarios, and the modeling conventions to be used.
2. Evaluate CO_2-flood performance for three technology scenarios using the CO_2-Prophet streamtube EOR screening model.
3. Develop life-cycle inventory of material and energy flows (including emissions) associated with EOR activity as defined by the model results.
4. Report results of streamtube modeling, life-cycle inventory, and related analysis of technology scenario alternatives.

16: OSAP-41817.401.01.01

Project Number	Project Title			
OSAP-41817.401.01.01	Assessment of Power Plants that Meet Proposed Greenhouse Gas Emission Performance Standards			
Contacts	**Name**	**Organization**	**Email**	
DOE/NETL Project Mgr.	Eric Grol	NETL – Office of Systems, Analysis, and Planning	Eric.Grol@NETL.DOE.GOV	
Principal Investigator	Eric Grol	NETL – Office of Systems, Analysis, and Planning	Eric.Grol@NETL.DOE.GOV	
Partners	Research and Development Solutions, LLC (RDS, an NETL site support contractor) NETL			
Stage of Development				
__ Fundamental	_X_ Applied R&D	__ Proof of Concept	__ Prototype Testing	__Demonstration

Technical Background:

In 2006, California passed legislation requiring that all baseload power generation come from sources that do not exceed the carbon dioxide (CO_2) emission rate of a natural gas combined cycle plant: 1,100 lb of CO_2 per net megawatt-hour (lb CO_2/net-MWh). Because demand in California exceeds supply, 21% of the power consumed in California is imported from neighboring states. This project seeks to determine how a coal-fired power plant in a neighboring state, which exports its product into California, may deal with this legislation.

This project presents the baseline cost and performance of a suite of coal-fired power plant configurations that are representative of units exporting power into California. For the purposes of this study, all plants are assumed to be sited in Wyoming. The study considers greenfield integrated gasification combined cycle (IGCC) plants, greenfield supercritical pulverized coal (PC) plants, and retrofit subcritical PC plants that limit CO_2 emissions to 1,100 lb CO_2/net-MWh and that achieve 90% CO_2 capture. For each plant type, this project modeled three cases:

- Baseline performance with no CO_2 capture
- CO_2 emissions reduced to 1,100 lb CO_2/net-MWh
- CO_2 emissions reduced by 90%

The Jim Bridger plant, located in Sweetwater County, Wyoming, was used as the basis for the subcritical retrofit cases. The plant was chosen as a typical example of a western coal-fired power plant that may be required to install controls to limit emissions to 1,100 lb CO_2/net-MWh. The elevation used was 6,700 ft, which is the average elevation of Wyoming. For consistency, this same elevation was used for all technologies. The fuel used in all nine cases was representative of a coal from the Powder River Basin (PRB).

The cost and performance of the various configurations will most likely determine which combination of technologies will be used to meet the demands of the power market. The selection of new generation technologies will depend on many factors, including the following:

- Capital and operating costs
- Overall energy efficiency
- Fuel prices
- Cost of electricity
- Availability, reliability, and environmental performance
- Current and potential regulation of air, water, and solid waste discharges from coal-fired power plants
- Market penetration of clean coal technologies that have matured and improved as a result of recent commercial-scale demonstrations under the DOE Clean Coal programs

PLANT OUTPUT

Net power output varies between technologies because the combustion turbines in the IGCC cases are manufactured in discrete sizes, but the boilers and steam turbines in the greenfield PC cases are readily available in a wide range of capacities. The net output in the subcritical retrofit PC plant is limited by the capacity of the existing boiler and steam turbine. The result is that all of the greenfield supercritical PC cases have a net output of 550 MW, the subcritical retrofit cases have net outputs ranging from 532 to 359 MW, and the IGCC cases have net outputs ranging from 502 to 401 MW.

The range in IGCC net output is caused by the increased elevation, the much higher auxiliary load imposed in the CO_2 capture cases primarily due to CO_2 compression, and the need for extraction steam in the water-gas shift reactions, which reduce steam turbine output. Higher auxiliary load and extraction steam requirements can be accommodated in the greenfield supercritical PC cases (larger boiler and steam turbine) but not in the IGCC or subcritical retrofit PC cases. For the IGCC cases or subcritical retrofit PC cases, it is impossible to maintain a constant net output from the steam cycle given the fixed input (combustion turbine for IGCC and existing boiler capacity for subcritical retrofit cases).

RESULTS SUMMARY

Plant Efficiency

- The IGCC no-capture case has the highest net efficiency of the technologies modeled in this study with an efficiency of 41.8%. The energy penalty for the 1,100 lb/net-MWh CO_2 emission level is smallest for IGCC and highest for the retrofit subcritical PC case.
- The energy penalty associated with adding carbon capture and sequestration to a new supercritical PC plant is greater than for a new IGCC plant. This was true for the 90% carbon capture case, as well as the 1,100 lb CO_2/net-MWh emissions case.
- The estimated efficiency of the existing subcritical PC plant is 32.6%. There is a 7.3% penalty to achieve the 1,100 lb/net-MWh CO_2 emission limit and a 10.6% penalty for the 90% capture case. The retrofit cases have the lowest efficiency for each of the three cases but the smallest energy penalty for the 90% capture case.

LEVELIZED COST OF ELECTRICITY (LCOE)

The LCOE results are summarized as follows:

- By virtue of having the initial plant capital investment paid off, the subcritical PC retrofit case has the lowest LCOE of all cases.

- Comparing the greenfield IGCC and PC cases without CO_2 capture, the LCOE of the PC case is 32% lower than the IGCC case.
- Comparing the greenfield IGCC and PC cases with CO_2 capture, the supercritical PC has the lowest LCOE of $120.01/MWh at a capture level to meet a CO_2 emissions level of 1,100 lb/net-MWh and $143.89/MWh at a capture level of 90%. The LCOEs of the supercritical PC cases are 20% and 18% lower than the corresponding IGCC cases.

Relationship to Program:

This project contributes to the development of cost/performance assessments of coal-fired power plants under a range of carbon capture targets within the CO_2 capture pathway of the NETL Carbon Sequestration Program. The benefits of performing this analysis are as follows:

- The analysis established the cost and performance of coal-fired power plants operating in the western United States, over a range of carbon capture targets. This enabled a comparison to plants operating in the eastern United States (determined in prior studies) which (1) highlighted important differences in site conditions between the two locations and (2) quantified their impacts on cost and performance.
- The analysis established the CO_2 capture requirement that is necessary for a coal-fired power plant to be approximately equal in CO_2 emissions to a natural gas combined cycle plant. Both cost and performance data at this emission limit were established.
- Cost and performance data for coal-fired power plants (new IGCC and PC, and PC retrofit) can be used to determine the effects of climate change legislation on the electric power industry in California. Dispatch curves based on the cost and performance generated from this study can determine how coal plants might dispatch in a carbon-constrained environment.

Primary Project Goal:

The goal of this project is to evaluate the cost and performance of coal-fired power plants, located in the western United States and burning PRB coal that separate and sequester plant CO_2 emissions.

California' Global Warming Solutions Act requires all baseload power generation to be from sources that do not exceed the greenhouse gas emissions of a natural gas combined cycle plant. The law would require coal-fired plants exporting their product into California to install controls to limit CO_2 emissions. The analysis conducted in this project attempted to quantify the cost and performance impacts of such plants capturing CO_2 emissions to be in compliance with the new law.

Objectives:

The primary objective of this analysis was to establish the cost and efficiency of coal-fired power plants that limit CO_2 emissions. Those limits were 0% carbon capture and storage (CCS), 90% CCS, and an emission rate of 1,100 lb CO_2/net-MWh. All cases were assumed to be located in the western United States and burning PRB coal.

APPENDIX F: LIST OF ACRONYMS AND ABBREVIATIONS

Acronym/ Abbreviation	Definition
°C	degrees Celsius
ASME	American Society of Mechanical Engineers
bcfy	billion cubic feet per year
BEG	Bureau of Economic Geology
BET	Brunauer-Emmett-Teller theory
BRTD	Board on Research and Technology Development
CASSM	Continuous Active Source Seismic Monitoring
CCC	Copyright Clearance Center
CCS	carbon capture and sequestration/storage
CFR	Code of Federal Regulations
Cl	chloride
CO_2	carbon dioxide
CO_2-EOR	carbon dioxide flood-enhanced oil recovery
CO_2-PENS	CO_2 Prediction of Engineered Natural Systems
CRTD	Center for Research and Technology Development
CU	City Utilities of Springfield
DC	dry combustion
DMA	direct memory access
DOE	U.S. Department of Energy
DOE-FE	U.S. Department of Energy Office of Fossil Energy
EOR	Enhanced Oil Recovery
FEHM	Finite Element Heat and Mass Transfer Code
FTIR	Fourier transform infrared
FY	fiscal year
GaPA	galactose pentaacetate
GCS	geologic carbon sequestration/storage
GlPA	glucose pentaacetate
GPC	gel permeation chromatography
GW	gigawatt
H_2	hydrogen
H_2S	hydrogen sulfide
ICP-ES	Inductively Coupled Plasma-Emission Spectrometry

Acronym/ Abbreviation	**Definition**
ICP-MS	Inductively Coupled Plasma-Mass Spectrometry
IGCC	integrated gasification combined cycle
INS	Inelastic Neutron Scattering
InSAR	Interferometric Synthetic Aperture Radar
JIP	joint industry project
Kr	krypton
LANL	Los Alamos National Laboratory
lb	pounds
LBNL	Lawrence Berkeley National Laboratory
LCOE	levelized cost of electricity
LLNL	Lawrence Livermore National Laboratory
LLS	Library Least Squares
LTI	Leonardo Technologies, Inc.
MDL	Minimum detectable limit
MO	Missouri
MOA	maltose octaacetate
Mt	megaton
MW	megawatt
MWh	megawatt-hour
N/A	not applicable
Na	sodium
NETL	National Energy Technology Laboratory
NF	nanofiltration
NMR	nuclear magnetic resonance
NRAP	National Risk Assessment Partnership
OCC	Office of Clean Coal
OMB	Office of Management and Budget
OSAP	Office of Systems Analysis and Planning
PAO	polyacetoxy oxetane
PBI	polybenzimidazole
PC	pulverized coal
PDMS	polydimethyl siloxane
PEGDME	polyethyleneglycol dimethylether

Acronym/ Abbreviation	**Definition**
PFPE	perfluoropolyethers
PI	principal investigator
Pitt	University of Pittsburgh
PPGDAc	polypropyleneglycol diacetate
PPGDME	polypropyleneglycol dimethylether
PRB	Powder River Basin
psi	pounds per square inch
psig	pound-force per square inch gauge
Q&A	question and answer
R&D	research and development
RCSP	Regional Carbon Sequestration Partnership
RO	reverse osmosis
$scCO_2$	supercritical CO_2
SECARB	Southeast Regional Carbon Sequestration Partnership
SF_6	sulfur hexafluoride
SimCCS	Spatial infrastructure model for CCS
SME	Society for Mining, Metallurgy, and Exploration
SO_2	sulfur dioxide
SO_4	sulfate
SSEB	Southern States Energy Board
SWSTP	Southwest Sewage Treatment Plant
syngas	synthesis gas
TDS	total dissolved solids
TOUGH2	Transport Of Unsaturated Groundwater and Heat
TOUGH-FLAC	Transport Of Unsaturated Groundwater and Heat-Fast Lagrangian Analysis of Continua
TTBB	tritertbutyl benzene
TTBP	tritertbutyl phenol
UOP	Universal Oil Products
UV-Vis	ultraviolet-visible
VCCER	Virginia Center for Coal and Energy Research
VSI	vertical scanning interferometry
VSP	vertical seismic profile

Acronym/ Abbreviation	Definition
WESTCARB	West Coast Regional Carbon Sequestration Partnership
WGSR	water-gas-shift reactors
ZERT	Zero Emission Research and Technology