Carbon Sequestration Project Portfolio
FY 2005

For PDF version, blue text contains a hyperlink to section or Fact Sheet within this document

Version Date:
April 26, 2005

NETL

Page left blank to accommodate 2-sided printing

Scott M. Klara
Technology Manager
U.S. Department of Energy
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
Phone: (412) 386-4864
Fax: (412) 386-4822
e-mail: scott.klara@netl.doe.gov

Sarah M. Forbes
Program Analyst
U.S. Department of Energy
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
Phone: (304) 285-4670
Fax: (304) 285-1301
e-mail: sarah.forbes@netl.doe.gov

Lowell Miller
Office of Fossil Energy
U.S. Department of Energy,
FE-24/Germantown Building
1000 Independence Avenue, S.W.
Washington, DC 20585-1209
Fax: (301) 903-2238
Phone: (301) 903-9451
e-mail: lowell.miller@hq.doe.gov

Jay Braitsch
Carbon Sequestration Planning & Analyses
Office of Fossil Energy
Department of Energy, FE-1
1000 Independence Avenue, S.W.
Washington, DC 20585
Fax: (202)586-4729
Phone: (202) 586-9682
e-mail: jay.braitsch@hq.doe.gov

Robert L. Kane
Carbon Sequestration Issue Manager
Office of Fossil Energy
Department of Energy, FE-26
1000 Independence Ave., S.W.
Washington, DC 20585
Fax: (202) 586-1188
Phone: (202) 586-4753
e-mail: robert.kane@hq.doe.gov

Carbon Sequestration Project Portfolio

FY 2005

Contact Sheet

Technical Program Contacts

Heino Beckert
Project Manager
U.S. Department of Energy
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880, Morgantown, WV 26507
Phone: (304) 285-4132 Fax: (304)285-440
e-mail : Heino.Beckert@netl.doe.gov

Charlie Byrer
Project Manager
U.S. Department of Energy
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880, Morgantown, WV 26507
Phone: (304) 285-4547 Fax: (304) 285-4403
e-mail: Charlie.Byrer@netl.doe

Dawn.Chapman
Project Manager
U.S. Department of Energy
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880, Morgantown, WV 26507
Phone(304) 285-4133 Fax: (304) 285-4403
e-mail: Dawn.Chapman@NETL.DOE.GOV

Karen Cohen
Project Manager
U.S. Department of Energy
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940, Pittsburgh, PA 15236
Phone: (412) 386-6667 Fax: (412) 386-5914
e-mail: Karen.Cohen@netl.doe.gov

Jose Figueroa
Project Manager
U.S. Department of Energy
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940, Pittsburgh, PA 15236
Phone: (412) 386-4966   Fax: (412) 386-4604
e-mail: Jose.Figueroa@netl.doe.gov

Timothy Fout
Project Manager
U.S. Department of Energy
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880 Morgantown, WV 26507
Phone: (304) 285-1341
e-mail: timothy.fout@netl.doe.gov

Philip.Goldberg
Project Manager
U.S. Department of Energy
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940 Pittsburgh, PA 15236
Office: (412) 386-5806
e-mail: Philip.Goldberg@NETL.DOE.GOV

David Hyman
Project Manager
U.S. Department of Energy
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940, Pittsburgh, PA 15236
Phone: (412) 386-6572 Fax: (304) 285-4403
e-mail: David.Hyman@netl.doe.gov

David.Lang
Project Manager
U.S. Department of Energy
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940 Pittsburgh, PA 15236
Phone: (412) 386-4881
e-mail : David.Lang@NETL.DOE.GOV

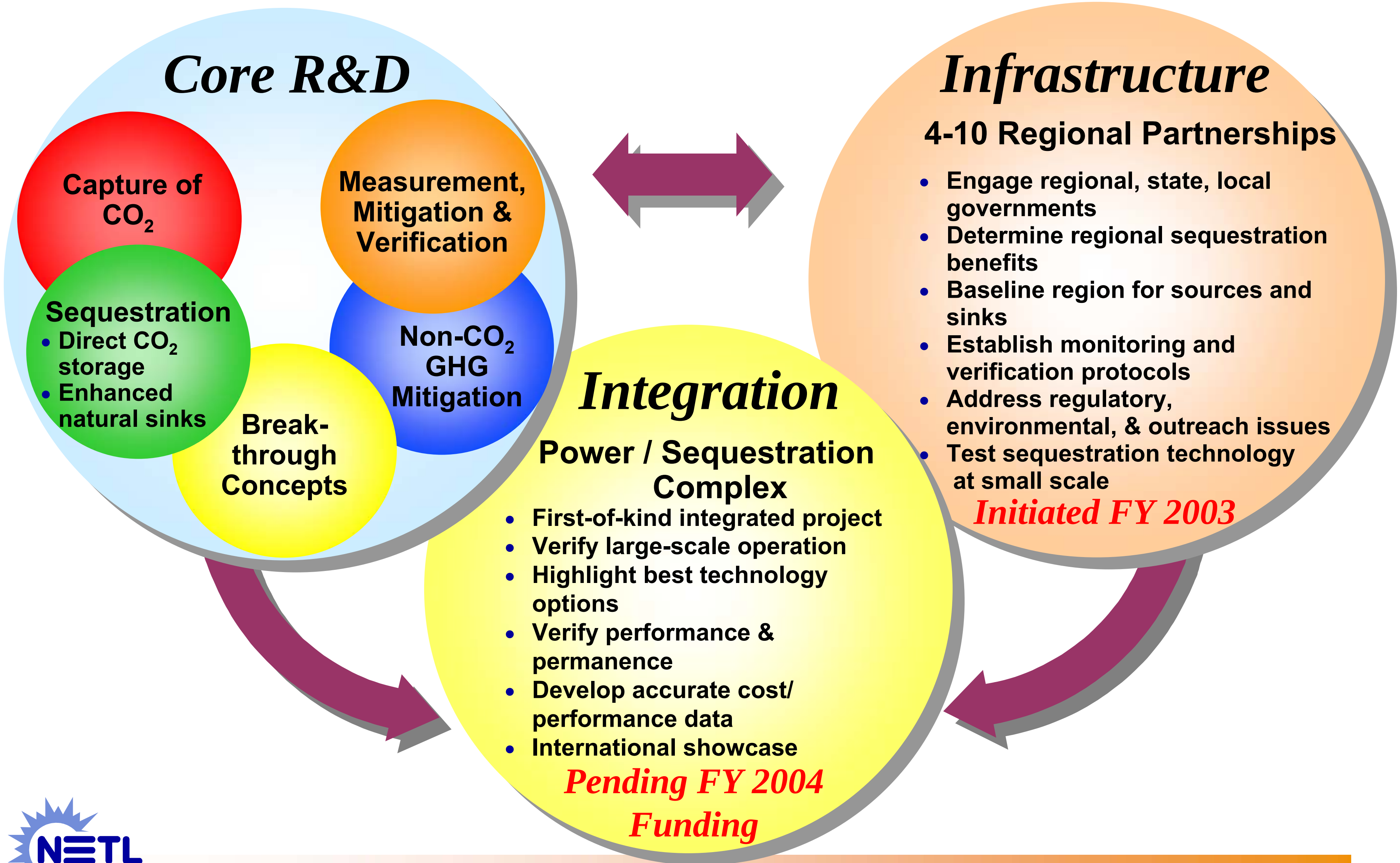
John Litynski
Project Manager
U.S. Department of Energy
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880, Morgantown, WV 26507
Phone: (304) 285-1339 Fax: (304) 285-4403
e-mail: John.Litynski@netl.doe.gov

Carbon Sequestration Project Portfolio

Carbon Sequestration Overview

Page left blank to accommodate 2-sided printing

Carbon Sequestration Program Structure

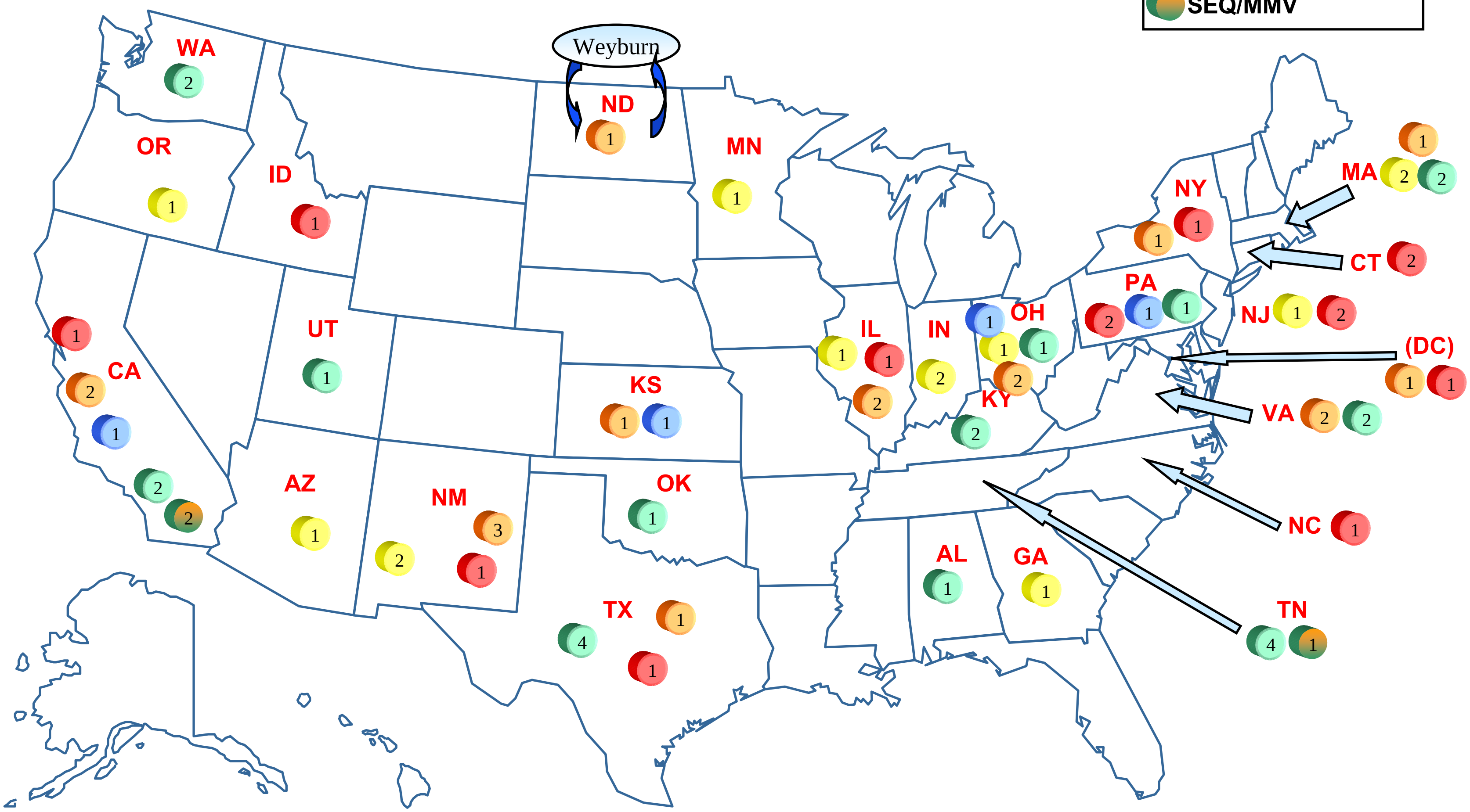


NETL

Carbon Sequestration Projects

LEGEND

- Capture of CO_2
- MMV
- Sequestration
- Breakthrough
- Non-CO_2
- SEQ/MMV



*Doesn't include NETL

State Projects Summary Table

State/Project Title	Primary Contractor	Area
Alabama		
Geologic Screening Criteria for Sequestration of CO_2 in Coal: Quantifying Potential of the Black Warrior Coalbed Methane in Fairway, Alabama	Alabama Geologic Survey	Sequestration
Arizona		
A Novel Approach To Mineral Carbonation: Enhancing Carbonation While Avoiding Mineral Pretreatment Process Cost	Arizona State University	Breakthrough
California		
CO_2 Hydrate Process for Gas Separation from a Shifted Synthesis Gas Stream	Nexant	Capture
A Sea Floor Gravity Survey of the Sleipner Field to Monitor CO_2 Migration	University of California, San Diego	MMV
Full-Scale Bioreactor Landfill	Yolo County	Non-CO_2
Feasibility of Large-Scale CO_2 Ocean Sequestration	Monterey Bay Aquarium Research Institute	Sequestration
Exploratory Measurements of Hydrate and Gas Compositions	LLNL	Sequestration
GEO-SEQ	LBNL	Seq/MMV
GEO-SEQ	LLNL	Seq/MMV
Low Cost Open-Path Instrument for Monitoring Atmospheric Carbon Dioxide at Sequestration Sites	California Institute of Technology	MMV
Connecticut		
Greenhouse Gas Emissions Control by Oxygen Firing in Circulating Fluidized Bed Boilers	ALSTOM Power, Inc.	Capture
Combined Power Generation and Carbon Sequestration Using a Direct Fuel Cell	FuelCell Energy, Inc.	Capture
District of Columbia		
A Collaborative Project to Develop Technology for Capture and Storage of CO_2 from Large Combustion Sources	BP Corporation	Capture
Stored CO2 & Methane Leakage Risk Assessment and Monitoring Tool Development: CO_2 Capture Project Phase 2	BP Corporation North America Inc	MMV
Georgia		
Process Design for the Biocatalysis of Value-Added Chemicals from CO_2	University of Georgia Research Foundation	Breakthrough
Idaho		
CO_2 Separation Using a Thermally Optimized Membrane	INEEL	Capture

NETL projects not included

State Projects Summary Table

State/Project Title	Primary Contractor	Area
Illinois		
CO_2 Capture for PC-Boiler Using Flue-gas Recirculation: Evaluation of CO_2 Capture/Utilization/Disposal Options	ANL	Capture
Carbon Dioxide Separation with Novel Microporous Metal Organic Frameworks	UOP L.L.C	Breakthrough
Indiana		
Design and Evaluation of Ionic Liquids as Novel Absorbents	University of Notre Dame	Breakthrough
A Novel Approach to Experimental Studies of Mineral Dissolution Kinetics	Indiana University	Breakthrough
Kansas		
MIDCARB (Interactive Digital Carbon Atlas)	University of Kansas Center for Research	MMV
Landfill Gas Sequestration in Kansas	Kansas Geological Survey	Non-CO_2
Kentucky		
Analysis of Devonian Black Shale in Kentucky for Potential Carbon Dioxide Sequestration and Enhanced Natural Gas Production	University of Kentucky Research Foundation	Sequestration
Carbon Sequestration on Surface Mine Lands	University of Kentucky	Sequestration
Massachusetts		
Recovery & Sequestration of CO_2 from Stationary Comb. Systems by Photosynthesis of Microalgae	Physical Sciences, Inc.	Breakthrough
Development of a Carbon Management Geographic Information System for the US	MIT	MMV
International Collaboration on CO_2 Sequestration (CO_2 Ocean injection)	MIT	Sequestration
Laboratory Investigations in Support of Carbon Dioxide-Limestone Sequestration in the Ocean	University of Massachusetts	Sequestration
Neutralizing Carbonic Acid in Deep Carbonate Strata Below the North Atlantic	Harvard University	Breakthrough
Minnesota		
A New Concept for the Fabrication of Hydrogen Selective Silica Membranes	University of Minnesota	Breakthrough
North Carolina		
Carbon Dioxide Capture from Flue Gas Using Dry Regenerable Sorbents	Research Triangle Institute	Capture
North Dakota		
Weyburn Carbon Dioxide Sequestration Project	Natural Resources Canada - CANMET	MMV

NETL projects not included

State Projects Summary Table

State/Project Title	Primary Contractor	Area
New Jersey		
Advanced CO_2 Cycle Power Generation	Foster Wheeler	Breakthrough
Conceptual Design of Optimized Fossil Energy Systems with Capture and Sequestration of CO_2	Princeton University	Capture
Conceptual Design of Oxygen-Based PC Boiler	Foster Wheeler	Capture
New Mexico		
Mineral Sequestration of CO_2 - Chemical Dissolution Approaches	LANL	Breakthrough
Thermally Optimized Membranes	LANL	Capture
Sequestration of CO_2 in a Depleted Oil Reservoir	Sandia National Laboratories	MMV
Sequestration of CO_2 in a Depleted Oil Reservoir	LANL	MMV
Ecosystem Dynamics and Econ. Anal	LANL	MMV
Applied Terrestrial Carbon Sequestration	LANL	MMV
Novel Dual Functional Membrane for Controlling Carbon Dioxide emissions from Fossil Fueled Power Plants	University of New Mexico	Breakthrough
New York		
Advanced Oxyfuel Boilers and Process Heaters for Cost Effective CO_2 Capture and Sequestration	Praxair, Inc.	Capture
Ohio		
Enhanced Practical Photosynthetic CO_2 Mitigation	Ohio University	Breakthrough
Experimental Evaluation of Chemical Sequestration of CO_2 in Deep Saline Formations	Batelle Columbus Laboratories	Sequestration
Carbon Sequestration in Reclaimed Mined Soils of Ohio	Ohio State Univeristy	MMV
Upgrading Methane Streams with Ultra-Fast TSA	Velocys, Inc	Breakthrough
Assessing Fossil Fuel and Recent Carbon Pools in Reclaimed Mined Soils	Ohio State University Research Foundation	MMV
Oklahoma		
Unmineable Coalbeds & Enhancing Methane Production Sequestering Carbon Dioxide	Oklahoma State University/Penn State University	Sequestration
Oregon		
CO_2 Mineralization	Albany Research Center	Breakthrough

NETL projects not included

State Projects Summary Table

State/Project Title	Primary Contractor	Area
Pennsylvania		
CO_2 Selective Ceramic Membrane for Water-Gas-Shift Reaction with Simultaneous Recovery of CO_2	Media and Process Technology Inc.	Capture
An Integrated Modeling Framework for Carbon Management Technologies	Carnegie Mellon University	Capture
Capture and Use of Coal Mine Ventilation Air Methane	CONSOL Energy Inc.	Non-CO_2
Enhanced Coalbed Methane Production and Sequestration of CO_2 in Unmineable Coal Seams	Consol	Sequestration
Tennessee		
Carbon Capture and Water Emissions Treatment System (CCWESTRS) at Fossil Fueled Electric Generation	Tennessee Valley Authority	Sequestration
Effects of Temperature and Gas Mixing in Underground Coalbeds	Oak Ridge National Laboratory	Sequestration
Enhancing Carbon Sequestration and Reclamation of Degraded Lands with Fossil Fuel Comb. ByProduct	ORNL	Sequestration
Enhanced Practical Photosynthesis Carbon Sequestration	ORNL	Sequestration
Geological Sequestration of CO_2 : GEO-SEQ	ORNL	Seq/MMV
Texas		
Carbon Dioxide Capture by Absorption with Potassium Carbonate	University of Texas at Austin	Capture
Maximizing Storage Rate and Capacity and Insuring the Environmental Integrity of Carbon Dioxide	Texas Tech University	Sequestration
CO_2 Sequestration Potential of Texas Low-Rank Coals	Texas Engineering Experiment Station	Sequestration
Optimal Geological Environments for Carbon Dioxide Disposal in Saline Aquifers	University of Texas at Austin (BEG)	Sequestration
Enhancement of Terrestrial C Sinks Through Reclamation of Abandoned Mine Lands in the Appalachians	Stephen F. Austin State University	Sequestration
Development of Science-Based Permitting Guidance for Geologic Sequestration of CO_2 in Deep Saline Aquifers Based on Modeling and Risk Assessment	University of Texas at Austin	MMV
Utah		
Reactive, Multi-phase Behavior of CO_2 in Saline Aquifers Beneath the Colorado Plateau	University of Utah	Sequestration

NETL projects not included

State Projects Summary Table

State/Project Title	Primary Contractor	Area
Virginia		
Natural Analogs for Geologic Sequestration	Advanced Resources International	MMV
Application and Development of Appropriate Tools and Technologies for Cost-effective Carbon Sequestration	The Nature Conservancy (TNC)	MMV
Application and Development of Appropriate Tools and Technologies for Cost-effective Carbon Sequestration	The Nature Conservancy (TNC)	MMV
Restoring Sustainable Forests on Appalachian Mined Lands for Wood Products, Renewable Energy, Carbon Sequestration, and Other Ecosystem Services	Virginia Polytechnic Institute and State University	Sequestration
Washington		
Enhancing Carbon Sequestration and Reclamation of Degraded Lands with Fossil Fuel Combustion ByProduct	PNNL	Sequestration
CO_2 Sequestration in Basalt Formations	PNNL	Sequestration

NETL projects not included

Page left blank to accommodate 2-sided printing

Carbon Sequestration

Technology Roadmap and Program Plan 2005

Developing the Technology Base and Infrastructure to Enable Sequestration as a Greenhouse Gas Mitigation Option

May 2005

A Message to our Stakeholders

The United States Department of Energy's (DOE) Carbon Sequestration Program continues to make progress toward its goals of lowering the cost of carbon dioxide (CO_2) capture and ensuring permanent and safe carbon storage. As sequestration technology has moved forward, the topic has attracted the interest of a wider community. These persons bring fresh perspectives, new ideas, and different expectations. The DOE welcomes these developments and is making the investment needed to accelerate the pace of technology progress. The following are highlights from the past year.

> ***Carbon management has become an increasingly important element of our coal research program. Carbon sequestration – the capture and permanent storage of carbon dioxide – has emerged as one of the highest priorities in the Fossil Energy research program.***
>
> Mark Maddox
> Principal Deputy Assistant Secretary for Fossil Energy
> March 16, 2005

- ***The Regional Carbon Sequestration Partnerships effort is progressing to Phase II.*** The first phase of the partnerships effort will end in June of 2005 as a clear success. Together the partnerships have established a national network of companies and professionals working to support sequestration deployments. They have created a carbon sequestration atlas for the United States, and have identified and vetted priority opportunities for sequestration field tests. The Phase II partnerships will build upon the Phase I effort. The Phase II solicitation, released in December of 2004, will provide up to $100 million in Federal funds over 4 years, with each partnership expected to receive between $2 million and $4 million per year. As in Phase I, each partnership will be required to provide at least 20 percent in cost-sharing over the duration of the project. More information about the Phase I partnerships is accessible through the document, "Regional Carbon Sequestration Partnerships: Phase I Accomplishments," which can be downloaded from the NETL website http://www.netl.doe.gov/coal/Carbon%20Sequestration/pubs/PhaseIAccomplishment.pdf

- ***A sustained investment in Core R&D is advancing the science.*** Three sample highlights from the last year: a more robust understanding of the full suite of mechanisms that can trap and immobilize CO_2 within geologic formations has emerged; field tests conducted at the Weyburn and Frio sites demonstrate an improved ability to "see" injected CO_2 in an underground formation and monitor its movement; and process engineering studies show that the combination of advanced amines and heat and pressure integration can reduce the steam use for amine post-combustion capture to as little at 1,200 Btu per pound of CO_2 captured. The program's project portfolio contains fact sheets and other information on a wide range of research activities. CD copies are available upon request and it can be downloaded from the NETL website http://www.netl.doe.gov/sequestration

- ***The non-CO_2 GHG control area is moving forward.*** Developments include promising laboratory-scale results for a temperature swing technology for capturing minemouth methane and a newly initiated project that will investigate the use of untreated landfill gas for enhanced coal bed methane recovery. This year's roadmap contains a separate table for non-CO_2 greenhouse gas control pathways and goals.

- ***The Program is proactively complying with environmental regulations.*** Project-level Environmental Assessments have been conducted under the National Environmental Policy Act (NEPA) for the geologic sequestration field projects at Frio, Texas and Marshall County, West Virginia. Also under NEPA, a Programmatic Environmental Impact Statement (EIS) is being conducted. In 2004 DOE hosted a series of public meetings in cities across the U.S. to explain the program's plans and goals and hear feedback from citizens. DOE released a Public Scoping Document in October 2004. Later in 2005, DOE will publish a draft EIS and then conduct a second round of public meetings. Copies of the reports and more information about the NEPA process is available at http://www.netl.doe.gov/coal/Carbon%20Sequestration/eis/index.html

- ***A global climate change curriculum is available.*** Recognizing the complexity of the Global Climate Change issue and the need to improve understanding of greenhouse gas mitigation options among the public, the Carbon Sequestration Program has funded a Global Climate Change curriculum for middle school students. Developed by the Keystone Center, the ten-day curriculum uses a variety of interesting and engaging activities to educate students on a range of topics including greenhouse gas science, the implications of day-to-day energy use choices, and the role of technology in mitigating GHG emissions. Group games, debates, and activities encourage children to consider the trade-offs among economics, social equity, and the environment. Teacher training sessions are held at National Science Teacher Association Conventions and at the Keystone Center and teachers throughout the country are using the curriculum in their classrooms. Building on the success of the middle school curriculum, a high school curriculum is currently under development. An online version of the curriculum is available at www.keystonecurriculum.org

Interaction with our stakeholders is critical to the success of the Sequestration Program. In 2005 the Program plans to engage stakeholders in a variety of ways, including the Fourth Annual Conference on Carbon Sequestration, the Annual Project Merit Review Meeting, the NEPA process, the Phase II Regional Partnerships, the educational curriculum, and the monthly carbon sequestration newsletter.

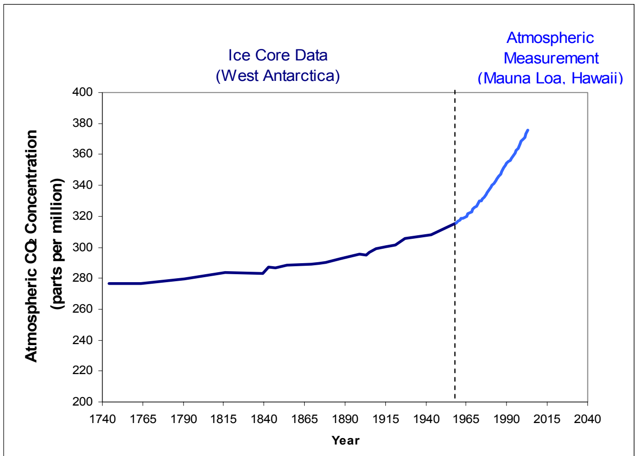
This document provides a vision of how to proceed with the development of carbon sequestration technology and is itself an important medium for engaging stakeholders. We invite readers to examine this document carefully and provide feedback to the contact persons listed on the back cover. Through a cooperative partnership of industry, academia, and government, we have the best chance of success in developing viable carbon sequestration options.

Chapter 1. Global Climate Change and the Role of Carbon Sequestration

Our modern economy and our associated quality of life – lighting, transportation, communications, heat and air conditioning – rely fundamentally on energy, and 85% of the energy consumed worldwide comes from the combustion of fossil fuels.

For nearly the first century of widespread fossil fuel use people did not pay much attention to carbon dioxide (CO_2) emissions. CO_2 was regarded, correctly, as a natural part of the Earth's atmosphere. However, sustained worldwide growth in population and economic activity have increased anthropogenic CO_2 emissions to the point where they are beginning to stress the natural carbon cycle. That is, more CO_2 is being exhausted than can be taken up by trees, grasses, and the oceans, and the excess is accumulating in the atmosphere. The concentration of CO_2 in the atmosphere is increasing at a rate of about 1-2 parts per million (ppm) per year. As shown in Figure 1, it is currently around 378 ppm, up 35% from the pre-industrial level of 280 ppm.

Figure 1. Atmospheric CO_2



Data sources: Ice core data obtained at the Siple Station, published by Friedli et al., 1986; Data from the Mauna Loa Observatory obtained from the NOAA web page.

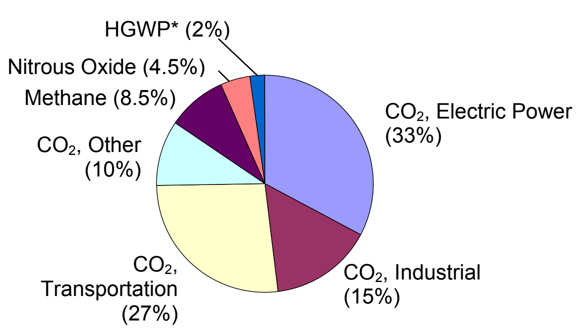
Elevated amounts of atmospheric CO_2 have two primary effects that are of concern to scientists. First, CO_2 in the atmosphere exerts a greenhouse effect that traps solar energy within the earth's ecosystem. An increased amount of greenhouse gases in the atmosphere may warm the planet overall and could cause unwelcome changes in regional climates. Second, increased CO_2 in the atmosphere causes an increased rate of CO_2 dissolution into ocean water which could make the oceans more acidic potentially causing damage to the ocean ecosystem. There is a great amount of uncertainty associated with the effects of greenhouse gas emissions and most of it centers on feedbacks. That is, how the earth's ecosystem will respond to increased atmospheric CO_2. A negative feedback pushes CO_2 back to its pre-industrial equilibrium value. For example, increased CO_2 in the atmosphere will cause trees to grow faster. Positive feedbacks are the opposite, for example increased global temperature may cause a polar tundra to thaw and release CO_2 in the atmosphere which increases the global temperature further and thaws more tundra in a spiraling effect.

Developing an understanding of the global climate, the carbon cycle, and the effects of atmospheric greenhouse gases (GHGs) is being pursued as a priority by the Administration through the U.S. Climate Change Science Program. In parallel the Administration is pursuing "transformational" technologies that provide traditional energy services (electricity, heat, transportation) without net greenhouse gas emissions or with very low greenhouse gas emissions. Carbon sequestration has emerged as a key technology option for GHG mitigation, alongside improved efficiency and non-carbon energy sources such as wind, biomass, hydro-electric, nuclear fission, and nuclear fusion. As a voluntary framework for progress, President Bush set forth the Global Climate Change Initiative (GCCI) in March of 2001. The GCCI sets a goal of an 18% reduction in the GHG intensity of the United States economy to be achieved by 2012. In 2012 an assessment will be conducted, and the DOE Carbon Sequestration Program seeks to have viable commercial options at that time that could potentially impact the GCCI reassessment.

Carbon sequestration is the capture and storage of CO_2 and other greenhouse gases that would otherwise be emitted to the atmosphere. The greenhouse gases can be captured at the point of emission, or they can be removed from the air. The captured gases can be used, stored in underground reservoirs or possibly the deep oceans, absorbed by trees, grasses, soils, and algae, or converted to rock-like mineral carbonates or other products. There are a wide range of sequestration possibilities to be explored, but a clear priority for near-term deployments is to capture a stream of CO_2 from a large, stationary emission point source and sequester it in an underground formation.

Carbon sequestration holds the potential to provide deep reductions in greenhouse gas emissions. Currently, a little less than half of total U.S. GHG emissions are large point sources of CO_2, Figure 2, and trends toward decarbonization of transportation fuels are increasing the amount of upstream CO_2 emissions. Research is ongoing to develop a clearer picture of domestic geologic sequestration storage capacity, but it is apparent that domestic formations have at least enough capacity to store several centuries worth of point source emissions. Technologies aimed at capturing and utilizing methane emissions from energy production and conversion systems fall within the definition of carbon sequestration and will reduce non-CO_2 greenhouse gas emissions. Mobile and dispersed GHG emissions can be offset by enhanced carbon uptake in terrestrial ecosystems, and research into CO_2 conversion and other advanced sequestration concepts will expand the range of sequestration further.

Figure 2. Greenhouse Gas Emissions in the United States, 2003



Roughly half of current GHG emissions are large CO_2 point sources in the power and industrial sectors that are amenable to capture and storage. Trends toward de-carbonization of transportation fuels will increase the percentage of future GHG emissions amenable to capture.

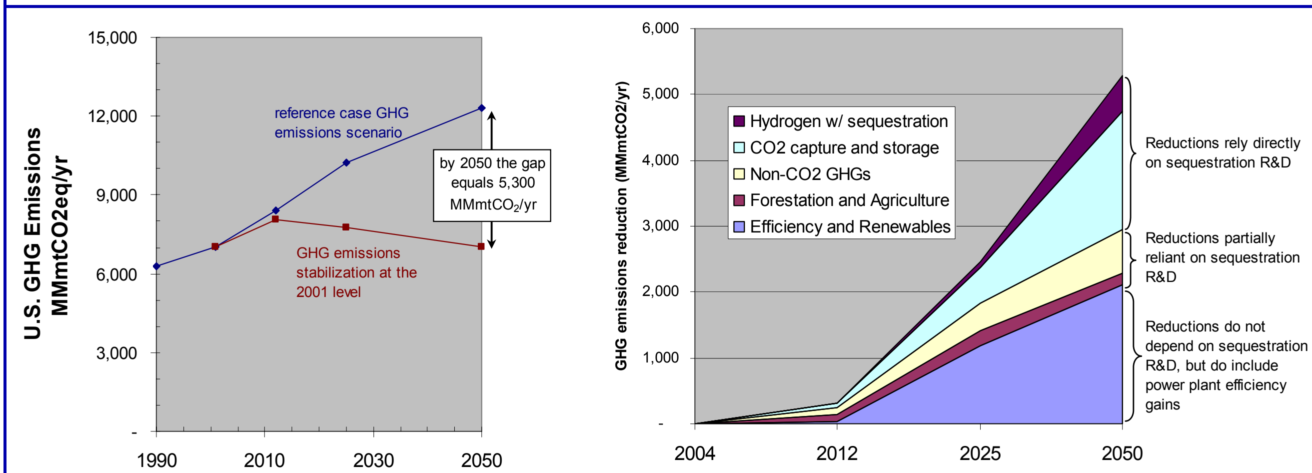
Source: DOE Energy Information Administration
Total 2003 U.S. GHG emissions were 6,891 million metrics tons CO_2 equivalent.
Methane, Nitrous oxide, and HGWPs reported in 100 year forcing CO_2 equivalents
** High global warming potential gases, e.g., certain refrigerants.*

DOE and the National Energy Technology Laboratory (NETL) have conducted analyses of energy supply and use in the United States to gauge both the need for carbon sequestration technology under a GHG emissions stabilization scenario and the ability of potential CO_2 sources and sinks to meet the need should it arise.

Figure 3 summarizes the results of that analysis. The top line on the left graphic in Figure 3 is a reference case GHG emissions scenario. It contains significant technology development for low or no-carbon fuels and improved efficiency, but no direct incentives for GHG emissions reduction. The lower line in Figure 3 is an emissions stabilization scenario. It contains accelerated improvement in GHG intensity through 2012 and then gradually reduced emissions thereafter toward a goal of stabilizing emissions at the 2001 level. The emissions reduction requirement, which equals the gap between the two scenarios, grows to 5,300 million metric tons of carbon dioxide per year by 2050. Emissions stabilization is a first step toward atmospheric concentration stabilization. Atmospheric concentration stabilization will require emissions to be reduced to 80-90 percent below current levels.

The right side of Figure 3 shows the contribution of various mitigation options needed to meet the gap under the emissions stabilization scenario. The contribution of each option has been estimated using an internal planning model that is based on cost/supply curves. The categories, "CO_2 capture and storage" and "Hydrogen with sequestration" are directly dependent on research conducted by the DOE Sequestration Program. Together, they account for 45 percent of total emissions reduction in 2050 under the emissions stabilization scenario. Terrestrial ecosystems and non-CO_2 GHG emissions control, which are being pursued by the DOE Sequestration Program in concert with other public and private partners, contribute another 15 percent. Clearly, carbon sequestration technology will play a pivotal role should GHG stabilization be deemed necessary.

Figure 3. U.S. GHG Emissions Scenarios . . . and Technologies to Fill the Gap



Chapter 2. Carbon Sequestration Technology Roadmap and Program Plan

VISION STATEMENT

To possess the scientific understanding of carbon sequestration options, and to provide cost-effective, environmentally-sound technologies that ultimately lead to a reduction in greenhouse gas intensity and stabilization of overall atmospheric concentrations of CO_2.

Recognizing the importance of carbon sequestration, the U.S. DOE established the Carbon Sequestration Program in 1997. The Program, which is administered within the Office of Fossil Energy by the National Energy Technology Laboratory, seeks to move sequestration technologies forward so that their potential can be realized and they can play a major role in meeting any future greenhouse gas emissions reduction needs. The Program directly implements the President's GCCI, as well as several National Energy Policy goals targeting the development of new technologies. It also supports the goals of the Framework Convention on Climate Change and other international collaborations to reduce greenhouse gas intensity and greenhouse gas emissions.

This document, the 2005 Carbon Sequestration Technology Roadmap and Program Plan, identifies research pathways that lead to commercially viable sequestration systems and sets forth a plan of action for sequestration research. The information is organized into three sections:

- ***A. Core R&D*** is the laboratory, pilot plant, and field work aimed at developing new technologies and new systems for GHG mitigation.
- ***B. Infrastructure Development*** is the groundwork for future carbon sequestration deployments being developed through the Phase I and Phase II Regional Partnership efforts.
- ***C. Program Management*** is the program's approach to R&D management: industry/government partnerships, cost-sharing, education and outreach, and environmental compliance.

Table 1 is a top-level roadmap for core R&D and infrastructure development. It shows progress toward the metrics for success achieved over the past year. The metrics and goals for CO_2 capture research are focused on reducing the cost and energy penalty because analysis shows that CO_2 capture drives the cost of sequestration systems. Similarly, the goals and metrics for carbon storage and measurement, monitoring, and mitigation (MM&V) are focused on permanence and safety. All three research areas work toward the overarching program goal of 90% CO_2 capture with 99% storage permanence at less than a 10% increase in the cost of energy services by 2012.

Table 1. Top-level Carbon Sequestration Roadmap

	Pathways	Metrics for Success		2005 Status, Progress thus Far
		2007	2012	
CO_2 Capture	• Post-combustion • Pre-combustion • Oxy-fuel	Develop at least two capture technologies that each result in less than a 20% increase in cost of energy services.	Develop at least two capture technologies that each result in less than a 10% increase in cost of energy services.	Heat and pressure integration combined with advanced amines have reduced steam consumption for post-combustion capture to 1,200 Btu/lb.
Sequestration/ Storage	• Hydrocarbon bearing geologic formations • Saline formations • Tree plantings, silvicultural practices, and soil reclamation • Increased ocean uptake	Field tests provide improved understanding of the factors affecting permanence and capacity in a broad range of CO_2 storage reservoirs.	Demonstrate ability to predict CO_2 storage capacity with +/-30% accuracy. Demonstrate enhanced CO_2 trapping at pre-commercial scale.	More robust understanding of CO_2 trapping and dissolution in saline water have been integrated into capacity estimation models.
Monitoring, Mitigation, &Verification	• Advanced soil carbon measurement • Remote sensing of above-ground CO_2 storage and leaks • Detection and measurement of CO_2 in geologic formations • Fate and transport models for CO_2 in geologic formations	Demonstrate advanced CO_2 measurement and detection technologies at sequestration field tests and commercial deployments.	CO_2 material balance greater than 99%. MM&V protocols enable 95% of stored CO_2 to be credited as net emissions reduction.	Test of time lapse (3D) seismic at Weyburn and Frio showed ability to detect volumes of CO_2 as small 2,500 metric tons within a geologic formation.
Breakthrough Concepts	• Advanced CO_2 capture • Advanced subsurface technologies • Advanced geochemical sequestration • Novel niches	Laboratory scale results from 1-2 of the current breakthrough concepts show promise to reach the goal of a 10% or less increase in the cost of energy, and are advanced to the pilot scale.	Technology from the program's portfolio revolutionizes the possibilities for CO_2 capture, storage, or conversion.	Seven awards from a competitive solicitation and a collaboration with the National Academies of Science were made in March 2004.
Non-CO_2 GHGs	• Minemouth methane capture/combustion • Landfill gas recovery	Deployment of cost-effective methane capture systems.	Commercial deployment of at least two technologies from the R&D program.	Promising lab-scale results for a temperature swing absorption process for methane/air separation.
Infrastructure Development	• Sequestration atlases • Project implementation plans • Regulatory compliance • Outreach and education	Phase II partnerships have pursued priority sequestration opportunities identified in Phase I and have conducted successful field tests.	Projects pursued by the Regional Partnerships contribute to the 2012 assessment under GCCI.	Data on CO_2 emissions point sources and sinks throughout the country are available at the NatCarb portal (www.natcarb.org). Phase II awards expected before the end of FY 2005.

A. Core R&D

The goal of the core R&D program is to advance sequestration science and develop to the point of pre-commercial deployment new sequestration technologies and approaches. The core program is a portfolio of work including cost-shared, industry-led technology development projects, research grants, and research conducted in-house at NETL. The core program is divided into the following five areas.

1. CO_2 Capture
2. Carbon Storage
3. Monitoring, Mitigation, and Verification (MM&V)
4. Non-CO_2 Greenhouse Gas Control
5. Breakthrough Concepts
6. Field Projects

The first three core research areas track the life cycle of a carbon sequestration system. That is, first CO_2 is captured, second it is stored or converted to a benign or useful carbon-based product, and third, the stored or converted CO_2 is monitored to ensure that it remains sequestered and appropriate mitigation actions are taken as needed. The fourth category, non-CO_2 greenhouse gas control, involves primarily the capture and reuse of methane emissions from energy production and conversion systems. The fifth area, breakthrough concepts, is a group of projects along the same general approach as the first four research areas, but with a higher technical uncertainty and the potential to expand the applicability of carbon sequestration beyond conventional point source emissions. Field projects are a verification of promising technologies across all areas and often involve the integration of more than one area. The goals and activities within each area are described in the pages that follow.

1. CO_2 Capture. CO_2 exhausted from fossil fuel-fired energy systems is typically either too dilute, at too low a pressure, or too contaminated with impurities to be directly stored or converted to a stable, carbon-based product. The aim of CO_2 capture research is to produce a CO_2-rich stream at pressure. The research is categorized into three pathways: post-combustion, pre-combustion, and oxyfuels. Post combustion refers to capturing CO_2 from a flue gas after a fuel has been combusted in air. Pre-combustion refers to a process where a hydrocarbon fuel is gasified to form a mixture of hydrogen and carbon dioxide and CO_2 is captured from the synthesis gas before it is combusted. Oxyfuel is an approach where a hydrocarbon fuel is combusted in pure or nearly pure oxygen rather than air, which exhausts a mixture of CO_2 and water which can easily produce pure CO_2.

Each of the three pathways has merit. Post-combustion capture applies to over 98% of current fossil fuel utilization assets, but it represents a significant technology challenge in that the CO_2 in flue gas is dilute (3-15 vol%), at low-pressure (15-25 psi), and often contaminated with traces of sulfur and particulate matter. A pre-combustion synthesis gas contains CO_2 in higher concentration (30-50 vol%), higher pressure (200-500 psi), and with less contaminants, but there are few gasification-based power systems currently in operation. Oxyfuel combustion requires roughly three times more oxygen per net kWh of power generation compared to gasification, and its efficiency is further compromised by the large amounts of flue gas that must be recycled to the combustion chamber for temperature control. However, oxyfuel does have a key advantage in that it can offer near 100% CO_2 capture. A breakthrough in membranes or chemical looping technology for oxygen delivery could dramatically change its prospects.

Table 2 presents a technology roadmap for CO_2 capture with performance goals that the Program has identified. The high partial pressure of CO_2 in synthesis gas allows for a wider range of pathways for pre-combustion. As shown in the table there are significant cross-cutting technology development areas which will enhance all CO_2 capture pathways. Table 2 also presents a set of technology performance goals identified by the program which, if achieved, provide a progression toward broad commercial viability of carbon sequestration.

The Program essentially accomplished its 2004 capture goal. American Air Liquide and Babcock & Wilcox performed oxycombustion experiments on a 1.5 MW pilot scale boiler and demonstrated a 70% reduction in CO_2 recycle per coal burned compared to a conventional 70/30 CO_2/oxygen base case.

Table 2. CO_2 Capture Roadmap

Technology Roadmap			Program Goals
CO_2 Capture Applications	**Priority Research Pathways**	**Cross Cut Pathways**	*Reduce cost and parasitic load*
Post-Combustion CO_2 capture	Chemical sorbents	Heat integration Improved base process efficiency Oxygen separation technology Gas/liquid contacting Integration of CO_2 capture with NO_x/SO_x/Hg/PM control	2004 Pilot-scale demo of 75% reduction in CO_2 recycle requirements. *GOAL MET 2007 Develop at least two capture technologies that each result in less than a 20% increase in cost of energy services. 2012 Develop at least four capture technologies that each result in less than a 10% increase in cost of energy services
Pre-Combustion CO_2 capture	Chemical sorbents Physical sorbents Membranes Water/CO_2 hydrates		
Oxyfuels	Oxygen/recycle flue gas boilers Chemical looping		

Table 3 presents a technology-centered analysis of CO_2 capture methods. In this framework CO_2 capture is divided into three sub-categories: CO_2 removal, CO_2 separation, and oxygen combustion. Each is defined as follows.

- *CO_2 removal*, bringing a CO_2-containing stream into contact with a compound that selectively captures a portion of the CO_2
- *CO_2 Separation,* the use of membranes to increase the concentration of a CO_2-containing stream
- *Oxygen combustion*, combustion of a fossil fuel with pure or highly pure oxygen to exhaust undiluted CO_2

Table 4 presents a list of projects currently being funded by the Carbon Sequestration Program, each categorized into the pathways contained in Table 3. Other programs within the Office of Fossil Energy are funding research in technologies related to CO_2 capture and those are not shown here. Table 4 presents a robust research portfolio. Links to web pages with more detailed information are provided for many of the projects.

Table 3. Technology-specific Breakdown of CO_2 Capture Options

	Technologies		Contact medium		Mechanism		Application	
CO_2 Removal	Chemical reaction	1	Aqueous solution	A	Temperature swing	1	Flue gas	F
	Dissolution	2	Hydrocarbon solution	B	Pressure Swing	2	Syngas	S
	Physical adsorption	3	Solid, fixed bed	C			Natural gas	G
	Hydrate formulation	4	Solid, moving bed	D			Other	O
			Solid, fluidized bed	E				
	Technologies		**Separation Type**		**Driving Force**		**Application**	
Separation	Permeability Difference	5	CO_2 permeate	P	Partial pressure differential	3	Flue gas	F
	Solubility Difference	6	CO_2 retentate	R	Delta pp, permeate-side reaction	4	Syngas	S
	Ion transport	7			Delta pp, retentate-side reaction	5	Natural gas	G
	Electrochemical	8					Other	O
	Technologies		**Combustion Temperature control**		**Combustion Pressure**		**Application**	
Oxygen Combustion	Cryogenic separation	9	Flue gas recycle	X	Atmospheric	6	Combustion, steam turbine	C
	O_2/N_2 membrane	10	Inert solid	Y	Medium, 50-200 psi	7	Gasification, comb. Cycle	G
	Metal oxide carrier	11			High, greater than 200 psi	8		

Table 4. CO_2 Capture Research Projects in Program Portfolio

Project Title	Performer	Roadmap categories				Web Links
Amines	Trimeric	1	A	1	F	
Sodium carbonate	CSSFA*	1	A	1	F	
Potassium carbonate	University of Texas	1	A	1	F	http://www.netl.doe.gov/publications/factsheets/project/Proj280.pdf
Supported amine	Advanced Fuel Research	1	C	1	F	
Aminated sorbents	CSSFA*	1	D	1	F	
Alkali carbonate	RTI	1	E	1	F	http://www.netl.doe.gov/publications/factsheets/project/Proj198.pdf
Microporous metal organic	UOP	3	C	1	F	
Pressure Swing Adsorption	CSSFA*	3	C	2	S	http://www.netl.doe.gov/publications/factsheets/project/Proj190.pdf
Temp. Swing Adsorption	CSSFA*	3	C	1	S	http://www.netl.doe.gov/publications/factsheets/project/Proj190.pdf
Hydrates	Nexant	4	A	1	S	http://www.netl.doe.gov/publications/factsheets/project/Proj196.pdf
Ionic liquid adsorbents	Notre Dame	3	A	1	F	
CO_2 selective membrane	Media Process Tech.	5	R	5	S	http://www.netl.doe.gov/publications/factsheets/project/Proj195.pdf
Hybrid membranes	CSSFA*	5	P	3	S	http://www.netl.doe.gov/publications/factsheets/project/Proj309.pdf
Hydrogen silica membrane	University of Minnesota	5	R	3	S	
Silica-based membrane	Sandia National Lab	5	P	4	F	
Thermally optimized	LANL, INEEL	6	R	3	F	http://www.netl.doe.gov/publications/factsheets/project/Proj194.pdf
Direct fuel cell	FuelCell Energy	8	P	3	F	
O_2-based PC boiler	Foster Wheeler	9	X	6	C	
Gasification w/ CO_2 recycle	Foster Wheeler	9	X	7	G	
O_2-fired CO_2 recycle retrofit	Southern Research Inst.	10	X	7	C	
O_2-enriched combustion	Praxair	10	X	7	C	http://www.netl.doe.gov/publications/factsheets/project/Proj197.pdf
Commercial fluidized bed	Alstom	11	Y	6	C	http://www.netl.doe.gov/publications/factsheets/project/Proj201.pdf
Novel fluidized bed	Alstom	11	Y	6	G	http://www.netl.doe.gov/publications/factsheets/project/Proj201.pdf

* Carbon Sequestration Science Focus Area (CSSFA)

2. Carbon Storage. Carbon storage is defined as the placement of CO_2 into a repository in such a way that it will remain stored (or sequestered) permanently. It includes three distinct sub-areas: geologic sequestration, terrestrial sequestration, and ocean sequestration. Each is described below, and Table 5 presents a synopsis of the carbon storage pathways and program goals.

CO_2 storage in geologic formations. The storage of CO_2 in a geologic formation (geosequestration) is the injection of CO_2 into an underground formation that has the capability to contain it securely. There are three categories of formations, each with different challenges and opportunities for CO_2 storage.

Oil and gas reservoirs. An oil or gas reservoir is a formation of porous rock that has held crude oil or natural gas (both of which are buoyant underground like CO_2) over geologic timeframes. It thus has a "demonstrated seal," and is fundamentally an ideal setting for CO_2 storage. The attractiveness of oil and gas reservoirs is often enhanced by the fact that injected CO_2 can enable the production of oil and gas resources left behind by primary recovery and water flood. A challenge is that well-known oil and gas fields have been drilled into extensively. Earlier wells were not sealed to today's high standards when they were abandoned, and most abandoned wells, old and recent, are plugged with Portland cement which is susceptible to corrosion from saline water with dissolved CO_2.

Saline formations. A saline formation is a formation of porous rock that is overlain by one or more impermeable rock formations and thus has the potential to trap injected CO_2. It is similar to an oil or gas formation with the exception that it has not actually held oil or gas over geologic time frames. Saline formations lack a demonstrated seal and do not offer the possibility for enhanced oil or gas production, but they have the advantage that they have not been penetrated by as many wells as oil and gas reservoirs.

Deep coal seams. CO_2 injected into a coal bed becomes adsorbed onto the coal's surfaces and is sequestered. Most coals contain adsorbed methane, and this methane can be recovered from coals that are too deep or too thin to mine economically. Coals preferentially adsorb CO_2 and, like enhanced oil recovery, CO_2 can be injected into an unmineable coal formation to enable recovery of residual methane not produced by de-pressuring. A challenge is that coals increase in volume when they adsorb CO_2, and coal swelling reduces permeability.

Saline formations are more commonplace than oil and gas formations or coal seams and, on the basis of total pore volume, saline formations offer the potential capacity to store hundreds of years worth of CO_2 emissions. Saline formations are the primary option for geosequestration should substantial storage capacity be needed in the future.

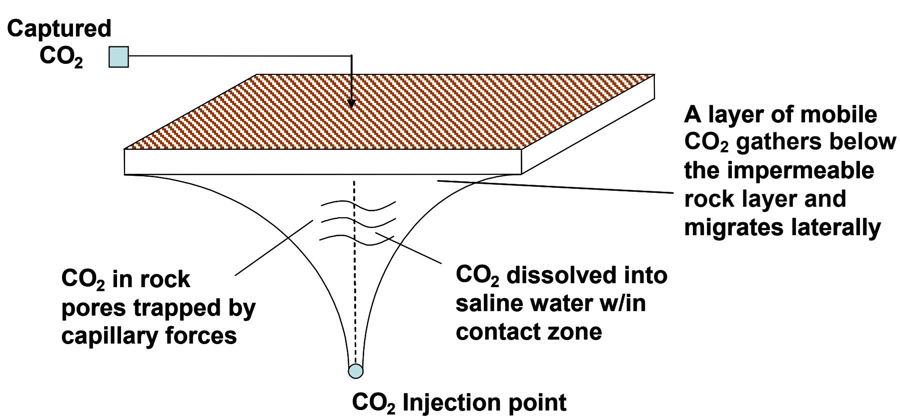
Table 5. Carbon Storage Roadmap

Technology Roadmap			Supporting Program Activities	
Current State of the Art	**Priority Research Pathways**	**Cross Cut Pathways**	**R&D Highlights**	**Program Goals** *Ensure permanence and ecosystem protection*
Geologic Sequestration 32 million tons of CO_2 per year are injected into depleting oil reservoirs in the U.S. as a part of enhanced oil operations, 10% is from anthropogenic sources. Current Commercial-scale geologic sequestration projects include: *Sleipner* (Norway, Statoil, 1996, 1 $MMtCO_2$/yr) *Weyburn* (Canada, ENCANA, 2000, 1.5 $MMtCO_2$/yr) *In Salah* (Algeria, BP, 2004, 1.2 $MMtCO_2$/yr)	Geologic formations Depleting oil reservoirs Unmineable coal seams Saline formations Depleting gas reservoirs Organically-rich shales Trapping mechanisms Structural containment Capillary trapping Dissolution in saline water Mineralization Adsorption on coal	Capability to predict CO_2 storage capacity Injection techniques to enhance CO_2 contact within a reservoir, preserve formation integrity, permeability CO_2-impermeable well bores	Completed an environmental assessment for CO_2 injection near Houston, TX, including a robust model of the injection site. Successfully injected 1,600 tons of CO_2 into a saline formation. A CO_2 ECBM field test at Tiffany, NM, demonstrated recovery of 1 scf of CBM per 3 scf CO_2 sequestered. Initiated a research project in which landfill gas will be injected into an unmineable coal bed to achieve methane/CO_2 separation, enhance CBM recovery, and sequester carbon.	2007 Conduct a CO_2 ECBM field test where CO_2 injectivity is maintained at 90% of its initial value to mitigate the negative effects of coal swelling. 2008 Develop an understanding of trapping mechanisms across oil reservoirs, coal seams, and saline formations. 2009 Initiate at least one large-scale demonstration of CO_2 storage (>1 million tons CO_2/year) in a geologic formation to demonstrate the capability to (1) predict compatibility to CO_2 injection and approximate storage capacity, and (2) achieve enhanced CO_2 trapping. 2012 CO_2 storage capacity prediction precision of ±30%.
Terrestrial Sequestration There are currently over 20,000 acres of forestland in the United States dedicated specifically to sequestering CO_2. The United States has 1.5 million acres of land damaged by past mining practices.	Planting trees instead of grass on mine land Soil reclamation using CCBs or other solid residuals No-till farming, aforestation, and other activities applied to a wide range of geographies to increase carbon uptake	Enhanced carbon transfer from plant to soil	Achieved 80% survival rate for tree plantings in both damaged land amended with flue gas desulfurization sludge (Paradise, KY) and in formerly compacted mineland (Hazard, KY).	2007 Develop optimization strategies and best practice guidelines for maximizing carbon sequestration potential on unproductive mine lands. 2008 Develop to the point of commercial deployment systems for advanced indirect sequestration of greenhouse gases that protect human and ecosystem health and cost no more than $10 per metric ton of carbon sequestered, net of any value-added benefits.
Ocean Sequestration No commercial deployments. Unknown ecosystem impacts. Enormous potential.	Ocean injection Deep injection technology Use of hydrates to increase permanence Ocean fertilization	Enhanced understanding & speculative technologies	An experiment conducted at a natural CO_2 vent in the ocean showed that fish can sense and avoid a plume of entrained CO_2. Laboratory tests have shown that premixing CO_2 and water prior to injection creates hydrates that are more dense than ocean water and sink upon injection.	Improved scientific understanding of this option.

CO_2 trapping within a geologic formation. Of emerging importance in the field of geosequestration is the science of maximizing CO_2 trapping mechanisms. At the temperatures and pressures of most underground formations (100 to 150 ^oF, 2,000 to 3,000 psi) CO_2 exists as a supercritical fluid - it has the density near that of a liquid but the viscosity near that of a gas. Supercritical CO_2 is lighter than the saline water in the formation and exhibits a strong tendency to flow upward. The primary method for trapping CO_2 is by a layer or “cap” of impermeable rock that overlies the formation of porous rock into which the CO_2 is injected and prevents upward flow of CO_2. It is called structural trapping and is the mechanism that caused natural deposits of crude oil, natural gas and CO_2. Four other mechanisms for CO_2 trapping described below can enhance the permanence of CO_2 storage within a geologic formation. Figure 4 shows how these advanced trapping mechanisms can apply in a typical CO_2 injection scenario.

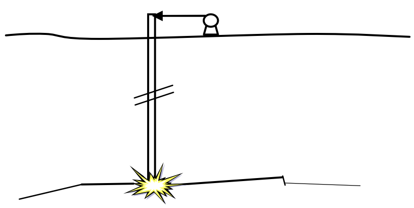
1. Capillary trapping. The surface of sandstone and other rocks preferentially adheres to saline water over CO_2. If there is enough saline water within a pore (75-90% of the pore volume), it will form a capillary plug that traps the residual CO_2 within the pore space.
2. Dissolution in saline water. CO_2 is soluble in saline water. As it comes in contact with the saline water it dissolves into solution.
3. Mineralization. Over longer periods of time (thousands of years), dissolved CO_2 reacts with minerals to form solid carbonates.
4. Adsorption of CO_2. Coal and other organically-rich reservoirs will preferably adsorb CO_2 onto carbon surfaces as a function of reservoir pressure.

Figure 4. CO_2 Storage Mechanisms

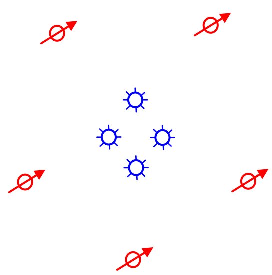


These advanced trapping mechanisms are only effective to the degree CO_2 comes into contact with the rock or coal within a formation. New injection techniques are being developed to maximize CO_2 contact within the reservoir. For example, accurate reservoir characterization can reveal the location of high permeability zones and enable placement of wells that force CO_2 flow through low permeability areas. Also, horizontal wells can enable multiple injection points along the bottom of a porous rock formation greatly increasing the lateral distribution of CO_2. Lateral distribution of CO_2 can also be enhanced through engineered fracturing of the rock. Several advanced drilling and injection techniques are shown in Figure 5.

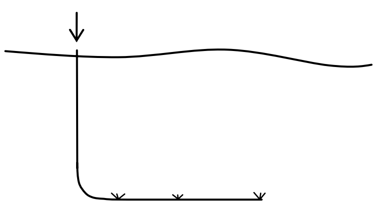
Figure 5. Examples of Advanced Drilling and CO_2 Injection Techniques



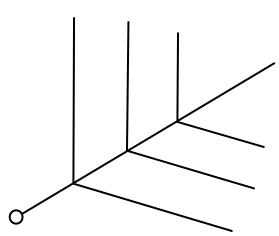
Hydrostatic pressure applied to a conventional vertical well can be used to engineer fractures in the rock that enable greater horizontal distribution of injected CO_2.



In the figure to the left five CO_2 injection wells (red) are positioned around the perimeter of a domed natural gas-bearing formation. CO_2 injected into the formation is drawn laterally toward the middle of the dome by the low pressure zone created by the natural gas recovery wells (blue). As it moves the CO_2 pushes residual natural gas toward the production wells, enhancing recovery. BP is testing this type of injection strategy in its In Salah project in Algeria.



Directional or horizontal drilling enables multiple injection points from one well and broad lateral distribution of injected CO_2. In a cost shared project with NETL, CONSOL will test/demonstrate the injection of CO_2 into an unmineable coal seam using a directional drilling technique.



In the figure to the left a patented pinnate horizontal well network is built from one surface well with multiple lateral diversions. The main stem can be up to 1,500 meters long with the offshoots offering a total of 9,000 meters of well length. A pinnate well network can produce 80% of coal bed methane in place within 3-4 years, and over 500 pinnate wells are currently in use worldwide for primary coal bed methane recovery. There is a possible opportunity to inject CO_2 into a pinnate network for storage after CBM production.

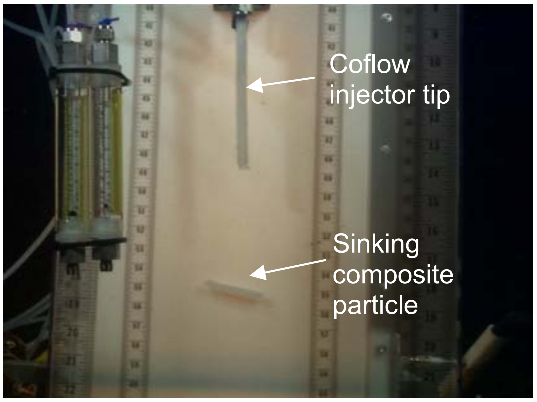
Terrestrial sequestration. Terrestrial sequestration is the enhancement of CO_2 uptake by plants that grow on land and in freshwater, and carbon storage in soils. Tree-plantings, no-till farming, forest preservation and other early activities provide an opportunity for low-cost CO_2 emissions offsets. More advanced research includes the development of fast-growing trees and grasses and deciphering the genomes of carbon-storing soil microbes. Responsibility for terrestrial sequestration research is shared by many Federal agencies, and the program coordinates its activities in this area with the DOE Office of Science, U.S. Department of Agriculture, and Department of Interior Office of Surface Mining.

One area of focus for the DOE's core sequestration R&D Program is in developing field practices for increasing carbon uptake in mined lands. With the passage of the Surface Mining Control and Reclamation Act of 1977 coal mine operators have moved away from reforestation of minelands in favor of compaction and grass planting. Compaction of the soil prevents tree growth because the roots need loose soil to grow in. The program is funding small field experiments with reforesting mineland, both planting trees on new, uncompacted minelands and ripping up compacted land and planting trees. The theory that a forest will provide increased carbon uptake per acre relative to grass lands is being tested in the field experiments and the cost per incremental ton of carbon stored estimated. The core program is also experimenting with the use of coal combustion by-products as soil amendments to repair damaged land.

Ocean sequestration. Ocean sequestration is examining methods that could potentially increase the carbon uptake of the oceans. One way to achieve increased ocean uptake is to enhance the growth of plants in the surface ocean, and a few years ago there was interest in the idea of fertilizing tracts of the oceans to increase algae growth. A field test revealed problems with fertilizer distribution and with the plant material decomposing to CO_2 in the surface ocean and being released back to the atmosphere.

The other option for ocean sequestration is to inject CO_2 into ocean water. The full extent of environmental risks associated with ocean injection are largely unknown at this time and injected CO_2 may not remain permanently sequestered. The core program is funding a limited amount of research in this area with the goal of better understanding the risks of ocean sequestration. As shown in Figure 6, the Program is also exploring methods to increase the storage permanence of injected CO_2 and to minimize its contact with the ocean ecosystems, including the formation of CO_2/water hydrates and mineral carbonates.

Figure 6. Injection of CO_2 Hydrate in Ocean Water 1,200 Meters Below the Surface.



The Monterey Bay Aquarium Research Institute (MBARI) has been conducting small scale experiments where liquid CO_2 is injected into ocean water (50 ml per minute). One of the goals of the experiments is to optimize the formation of dense CO_2/water hydrates. These hydrates sink in deep ocean water and provide a greater residence time for injected CO_2. Another goal is to develop and test instruments to "see" the injected CO_2 in situ and monitor its effects on ocean water, for example Raman spectroscopy.
Source: C. Tsouris, P. Brewer, E. Adams et al.; Jan 2005.

3. Monitoring, Mitigation, and Verification (MM&V). Monitoring and verification are defined as the capability to measure the amount of CO_2 stored at a specific sequestration site, monitor the site for leaks or other deterioration of storage integrity over time, and to verify that the CO_2 is stored in a way that is permanent and not harmful to the host ecosystem. Mitigation is the capability to respond to CO_2 leakage or ecological damage in the unlikely event that it should occur. MM&V is broken into two categories (1) geologic sequestration and (2) terrestrial sequestration. This structure is changed from the 2004 roadmap to reflect the fundamental differences in the suite of technology pathways for MM&V for terrestrial ecosystems versus geologic formations. Research activities in both areas are closely coordinated with the associated work in carbon storage. In addition to ensuring effective and safe storage, MM&V provides information and feedback that is useful in improving and refining storage field practices. Ocean sequestration is in an earlier stage of development and does not yet have an MM&V component. Table 6 shows goals and research pathways for geologic and terrestrial MM&V. Each area is described below.

MM&V technologies for CO_2 storage in geologic formations. Monitoring and verification for geosequestration contains three components:

Modeling. Modeling is the understanding of the forces that influence the behavior of CO_2 in a reservoir, and the simulation of that understanding in a computer program that enables one to predict the fate and transport of injected CO_2. Modeling is important due to the very fundamental fact that a geosequestration project operator will need to prove with a high degree of confidence that injected CO_2 will remain securely stored before injection is allowed to commence. Modeling is a complex undertaking that involves the flow of CO_2 through heterogeneous rock; dissolution, capillary trapping, chemical reactions; and the impact of the CO_2 plume and increased pressure on the formation cap rock. The boundary of a robust CO_2 storage model is not limited to the target formation, but also includes fugitive paths that CO_2 may travel up to the surface. The program seeks to acquire the data needed to support the models (e.g., chemical reaction kinetics, and two and three phase vapor/liquid equilibrium data at super critical conditions) and to develop integrated models that support the needs of planned field tests.

Plume tracking. Plume tracking is the ability to “see” the injected CO_2 and its behavior. Seismic has risen up as a key technology in this area. Supercritical CO_2 is more compressible than saline water and sound waves travel through it at a different velocity. Thus free CO_2 in a saline formation leaves a bright seismic signature, as seen at the Weyburn and Frio field tests, Figure 7. Observation wells are another important source of information for plume tracking.

Leak detection. CO_2 leak detection systems will serve as a backstop for modeling and plume tracking. The first challenge for leak detection is the need to cover large areas. The CO_2 plume from an injection of 1 million tons CO_2 per year in a saline formation for twenty years could be spread over a horizontal area of 15 square miles or more. The second challenge is to separate out CO_2 leaks from the varying fluxes of natural CO_2 respiration.

There are important interconnections among the three areas. For example, data from plume tracking enables validation of reservoir models. On the other hand a robust reservoir model enable operators to better interpret data from plume tracking. Models and plume tracking combine to help focus leak detection efforts on high-risk areas.

Figure 7. Time-lapse Seismic CO_2 Monitoring Conducted at the Weyburn Field

The figure above shows the results of a seismic assessment conducted at the Weyburn oil field in Saskatchewan, Canada. The horizontal lines are layers of sedimentary rock that were identified in a pre-injection baseline analysis of the formation. This seismic reading was taken after CO_2 injection had begun, and the splotches of green and yellow show regions within the formation where sound waves travel through the rock at relatively slower speeds - a strong indication of the CO_2 plume location. Source: PRTC, "IEA GHG Weybun CO_2 Monitoring & Storage Project, 2000-2004 Report," Sept., 2004.

Mitigation. If CO_2 leakage occurs, steps can be taken to arrest the flow of CO_2 and mitigate any negative impacts. Examples include lowering the pressure within the CO_2 storage formation to reduce the driving force for CO_2 flow and possibly reverse faulting or fracturing; forming a "pressure plug" by increasing the pressure in the formation into which CO_2 is leaking; intercepting the CO_2 leakage path; or plugging the region where leakage is occurring with low permeability materials using for example "controlled mineral carbonation" or "controlled formation of biofilms."

MM&V for terrestrial ecosystems. The area of MM&V for terrestrial ecosystems contains three components:

Organic Matter Measurement. Conventional technologies for organic matter measurement (i.e., tree trunk diameter measurement and vegetation and soil samples) are too labor intensive for large-scale deployments. Advanced MM&V technologies such as arial videography rely on technology and can provide a significantly more robust site characterization at lower cost. Working with The Nature Conservancy the program is developing a next generation of satellite-based imaging technology.

Soil Carbon Measurement. Soil carbon offers the potential for long-term secure storage. The program is developing automated technologies for measuring soil carbon.

Modeling. Detailed models are used to extrapolate the results from random samples to an entire plot and to estimate the net increase in carbon storage relative to a case without enhanced uptake. Economic models show accumulations of emissions credits and revenues versus an initial investment.

Table 6. MM&V Roadmap

<table>
<tr><th colspan="3">Technology Roadmap</th><th colspan="2">Supporting Program Activities</th></tr>
<tr><th colspan="2">Pathways</th><th>Cross-cut Pathways</th><th>Research Highlights</th><th>Goals</th></tr>
<tr><td>Geologic Formations</td><td>Modeling
Reservoir models (CO_2 flow from target to vadose)
Geochemical models
Geomechanical models
Plume tracking
Surface to borehole seismic
Micro-seismic
Cross well tomography
Reservoir pressure monitoring
Observation wells/fluid sampling
CO_2 leak detection
Vadose zone soil/water sampling
Air sample/gas chromospectrometry
Infrared-based CO_2 in air detectors
Vegetation growth rates
CO_2 tracers, natural and introduced
Well testing
Sub-surface monitoring wells
Mitigation
De-pressure target formation
Pressure, permeability plug
Interception, pump and treat</td><td rowspan="2">Integrated flow, geochemical, and geomechanical models
Ecosystem response models
Model use to focus monitoring on higher-risk leakage areas
Risk analysis protocols
Protocols for using advanced MM&V technologies in commercial systems</td><td>3D seismic tests conducted at the Weyburn field show the ability to detect volumes of CO_2 within the geologic formation as small as 2,500 metric tons.

Completed a rigorous flow model of CO_2 injection into the Frio Saline Formation.

Completed a micro-gravimetric survey of Sleipner Utsira saline formation.</td><td rowspan="2">2006 Apply promising MM&V technologies to at least several sequestration field tests or commercial applications.

2008 An MM&V protocol enables 95% of CO_2 uptake in a terrestrial ecosystem to be credited and represents no more than 10% of the total sequestration cost.

2012 CO_2 material balance greater than 99%.

2012 An MM&V protocol enables 95% of CO_2 injected into a geologic reservoir to be credited.</td></tr>
<tr><td>Terrestrial Ecosystems</td><td>Modeling
Above/below ground correlations
Cash flow models of terrestrial sequestration
Plant matter measurement
Multi-spectral 3-dimensional ariel digital imagery
Satellite imagery
Light Detection and Ranging (LIDAR)
Soil carbon measurement
Laser-induced breakdown spectroscopy (LIBS)
Inelastic Neutron Scattering Soil Carbon Analyzer</td><td>Completed flyovers of the Delta National Forest in Mississippi to measure carbon storage.

Complete construction and testing of person portable LIBS.

Complete calibrations of scanning system.</td></tr>
</table>

4. Non-CO_2 Greenhouse Gas Control. Because non-CO_2 greenhouse gases (e.g., methane, N_2O, and high global warming potential gases) can have significant economic value, emissions can often be captured or avoided at relatively low net cost. The Sequestration Program is focused on fugitive methane emissions where non-CO_2 greenhouse gas abatement is integrated with energy production, conversion, and use. Landfill gas and coal mine methane are two priority opportunities. Landfill gas is typically half methane, half CO_2, with small amounts of heavier hydrocarbons. Technologies include end-of-pipe separations to concentrate the methane, and landfill engineering to produce a more useful gas stream over a shorter period of time. Coal mine methane is much more dilute (0.3 – 1.5% methane in air) and represents a larger challenge. Methane can be captured for use or oxidized to CO_2 which has a much lower GHG effect per molecule. Table 7 presents a roadmap for non-CO_2 GHG control research and several projects funded by the Program.

Table 7. Non-CO_2 GHG Roadmap

	Technology Pathway	Supporting Research Projects	Program Goals
Landfill Gas	Methane/nitrous oxide generation control Water management Microbe management Methane/CO_2 separation Bacterial oxidation of CH_4 and N_2O Use of landfill gas for ECBM	Methane recovery from landfills [Yolo County Planning and Public Works Department] http://www.netl.doe.gov/publications/factsheets/project/Proj199.pdf Methodologies to minimize microbial production of nitrous oxide and maximize microbial consumption of methane in landfill cover soils [University of Michigan] Maximize biodegradation and minimize the formation of methane by controlled injection of air and liquids [University of Delaware] Design and test a landfill tarp impregnated with immobilized methane oxidizing bacteria [University of North Carolina] Injection of landfill gas into un-mineable coal seams [Kansas Geological Survey] http://www.netl.doe.gov/publications/factsheets/project/Proj324.pdf	2007 Effective deployment of cost-effective methane capture systems 2012 Commercial deployment of at least two technologies from the R&D program
Coal Mine Methane	Separation of methane in air at a concentration of 0.3-1.5 vol% Catalytic oxidation of methane in air at a concentration of 0.3-1.5 vol%	Catalytic combustion of minemouth methane http://www.netl.doe.gov/publications/factsheets/project/Proj248.pdf Nitrogen/methane separation via ultra-fast thermal swing adsorption http://www.netl.doe.gov/publications/factsheets/project/Proj253.pdf	

5. Breakthrough Concepts. Breakthrough Concepts R&D is pursuing revolutionary and transformational sequestration approaches with potential for low cost, permanence, and large global capacity. These concepts are very speculative but have the potential to provide "leap frog" performance and cost improvements compared to existing technologies**.**

CO_2 conversion is an important part of the portfolio for Breakthrough Concepts. CO_2 can be converted into benign solids to provide permanent storage or back to a hydrocarbon fuel to provide a regenerable energy system using carbon as the energy source. A guiding principal is to mimic and harness processes found in nature, for example, photosynthesis and mollusk shell formation.

Chemical Looping

Chemical looping is a "breakthrough" approach to fossil fuel conversion that has received significant attention. In a chemical looping process, oxygen for combustion is delivered to the fuel via a redox agent rather than by direct air or gaseous oxygen, providing the potential for high-efficiency fuel conversion and venting a high-purity CO_2 exhaust at pressure.

In 2004/2005 the Program explored chemical looping gasification concepts, where the redox agent supplies substoichiometric oxygen for gasification of fuel. These concepts are complex but offer the step change in efficiency associated with combined cycle power plant technology.

6. Field Projects. Field projects are an important part of the program's technology development effort. Conditions in both terrestrial ecosystems and geologic formations are difficult to simulate, and so testing of ideas in the field often enables significant learning and insight. Sequestration field tests provide a test bed for CO_2 detection and measurement technologies and also an opportunity to ground-truth models. Field tests also bring technology developers and communities together to address concerns about the environmental impacts of sequestration deployments and to determine the performance standards that must be met. Figure 8 presents a partial list of program-funded field tests in different stages of planning and execution.

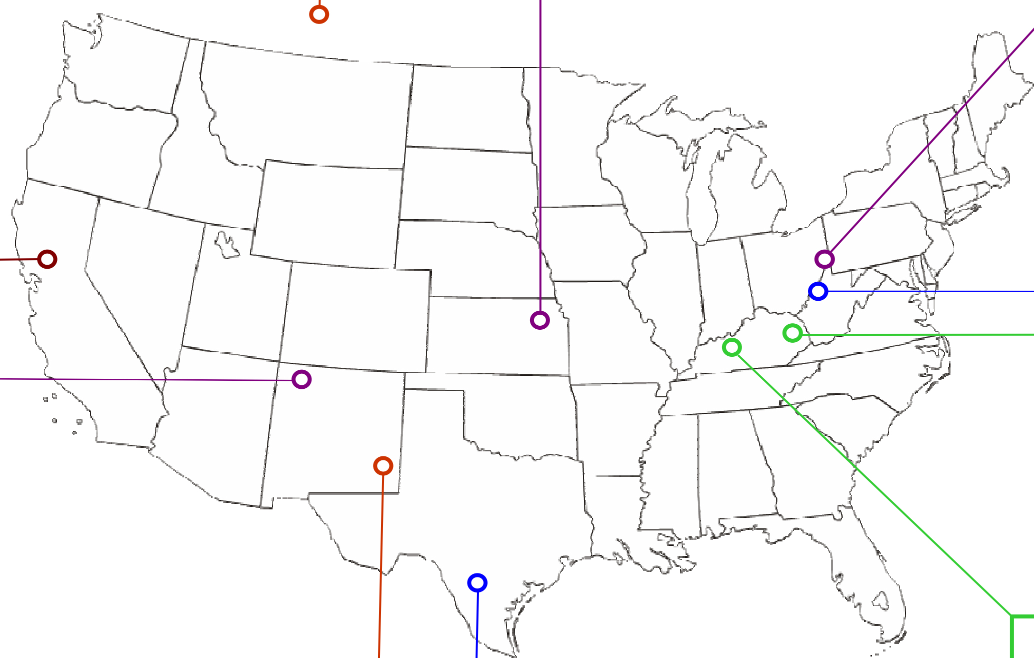
Figure 8. Carbon Sequestration Field Projects

WEYBURN, CANADA
Lead: ENCANA
Type: Geologic, Depleting oil reservoir
Phase: Injection began in 2001
Scale: 20 MM tons CO_2 over 15 yrs
Highlights: Demonstrate use of time lapse (3D) seismic and other technologies to monitor CO_2.
http://www.netl.doe.gov/publications/factsheets/project/Proj282.pdf
http://www.encana.com/operations/upstream/ca_weyburn.html

JOHNSON COUNTY, KS
Lead: Kansas Geologic Survey
Type: Geologic, coal seam
Phase: Pre-injection
Scale: TBD
Highlights: Will explore the possibility of injecting untreated landfill gas (50/50 CO_2/CH_4) into a coal bed for both enhanced CBM recovery and landfill gas purification.
http://www.netl.doe.gov/publications/factsheets/project/Proj324.pdf

MARSHALL COUNTY, WV
Lead: Consol Energy
Type: Geologic, coal seam
Phase: Pre-injection, 2005 injection planned
Scale: 26,000 tons CO_2 over 1 year
Highlights: Plan to demonstrate horizontal CO_2 injection wells with up to 3,000 feet of horizontal length.
http://www.consolenergy.com/content.asp?c=GreenhouseGasManagement_20030613113634

YOLO COUNTY, CA
Lead: Yolo County Planning and Public Works Dept.
Type: Non-CO_2, LFG
Phase: Construction of test cells completed
Scale: 12 acres
Highlights: Seek to demonstrate LFG generation over 5-10 years as opposed to typical 10-30 years for more economical recovery.
http://www.netl.doe.gov/publications/factsheets/project/Proj199.pdf



NEW HAVEN, WV
Lead: American Electric Power
Type: Geologic, Saline formation
Phase: Pre-injection
Scale: TBD
Highlights: Injection well revealed low permeability in target zone; evaluating potential storage capacity in shallower formations.

SAN JUAN BASIN, NM
Lead: Burlington Resources, Advanced Resources International
Type: Geologic, coal seam
Phase: Post-injection
Scale: 280,000 tons CO_2 over 6 years
Highlights: Developed improved understanding of coal swelling and ability to predict CO_2 storage capacity.
http://www.netl.doe.gov/publications/factsheets/project/Proj228.pdf

HAZARD, KY
Lead: University of Kentucky
Type: Terrestrial, tree planting
Phase: Third year of planting
Scale: 500 acres
Highlights: Demonstrated increase site indices and sequestration while increasing water infiltration and reducing sediment runoff with tree planting in uncompacted or ripped mineland.

WEST PEARL QUEEN, NM
Lead: Strata Production
Type: Geologic, Depleting oil reservoir
Phase: Post-injection
Scale: 2,200 tons CO_2 over 42 days
Highlights: Tested tracer and seismic MM&V; examined alternative CO_2 trapping mechanisms.

FRIO, TX
Lead: University of Texas Bureau of Economic Geology
Type: Geologic, Saline formation
Phase: Post-injection
Scale: 1,800 tons CO_2 over 3 weeks
Highlights: Developed a thorough Environmental Assessment under NEPA.
http://www.beg.utexas.edu/environqlty/co2seq/fieldexperiment.htm

PARADISE, KY
Lead: Tennessee Valley Authority
Type: Terrestrial, tree planting
Phase: Post-planting, second growing season
Scale: 100 acres
Highlights: Achieved 80% survival rate for maple poplar, sweet gums, and sycamore using FGD sludge as amendment and irrigating with FGD settling pond water.
http://www.netl.doe.gov/publications/factsheets/project/proj134.pdf

B. Infrastructure Development

Regional Partnerships

DOE initiated seven Regional Carbon Sequestration Partnerships (RCSPs) in September of 2003 with the goal of developing an infrastructure to support and enable future carbon sequestration field tests and deployments. The first phase of the RCSPs will end in June of 2005 as a clear success. Together the partnerships have established a national network of companies and professionals working to support sequestration deployments, they have created a carbon sequestration atlas for the United States, and identified and vetted priority opportunities for sequestration field tests. Table 8 presents an overview of the Phase I partnerships. More information about them is accessible via the web links in Table 8 or through the document, "Regional Carbon Sequestration Partnerships: Phase I Accomplishments," which can be downloaded from the NETL website http://www.netl.doe.gov/coal/Carbon%20Sequestration/pubs/PhaseIAccomplishment.pdf

> One of the cornerstones of our carbon sequestration program, a national network of regional partnerships, will continue its important work in FY 2006. This Secretarial initiative has brought together the federal government, state agencies, universities, and private industry to determine which options for capturing and storing greenhouse gases are most practical for specific areas of the country.
>
> Mark Maddox
> Principal Deputy Assistant Secretary for Fossil Energy
> March 16, 2005

In December 2004, DOE announced an open competitive solicitation for Phase II RCSPs. The Phase II partnerships will be four years in duration with an expected Federal funding per award of $2-4 million per year. Like Phase I, the Phase II awards require a minimum cost share of 20%. Proposals were accepted on March 16, 2005 and awards are expected to be announced before the end of FY 2005.

The primary and overarching objective of the Phase II Regional Partnerships will be to move forward with priority sequestration technology validation tests identified in the Phase I effort. Successful implementation of these tests will support the 2012 assessment under the Administration's Global Climate Change Technology Initiative and will provide direction and focus on viable large-scale sequestration deployments within the regions. Supporting the primary objective will be the refining and implementing of MM&V protocols, developing an improved understanding of environmental and safety regulations, establishing protocols for project implementation, accounting, and contracts, and conducting public outreach and education. Also in Phase II, partnerships will seek to continue the characterization of the regions and to refine a national atlas of carbon sources and sinks.

In FY 2009 DOE will consider an optional Phase III effort for the RCSPs. The third phase, which would run through 2013, is contingent upon continued importance/synergies to the FutureGen initiative, the need for the validation of additional sequestration sites throughout the United States, and budget availability.

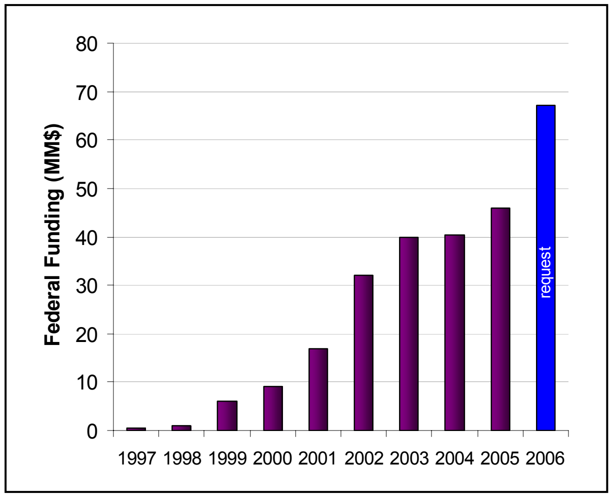
Table 8. Phase I Regional Sequestration Partnerships At-A-Glance

	Lead Organization/ Webpage	Highlights
westcarb.org	California Energy Commission http://www.westcarb.org/	• Identified candidate enhanced coal bed methane and enhanced oil recovery projects • Detailed assessment of forestation as mitigation by storage, fire management, and biofuel opportunities
Southwest Regional Partnership on Carbon Sequestration	New Mexico Institute of Mining and Technology http://www.southwestcarbonpartnership.org/	• Resource-rich region with two CO_2 pipelines • Identified seven candidate sites for field testing • Conducted web-based "town hall" meetings
Big Sky Carbon Sequestration Partnership	Montana State University http://www.bigskyco2.org/	• Large storage potential in basalt formations • Focus on agriculture and forestry project protocols to increase salability of credits • Close interaction with state governments
The Plains CO_2 Reduction Partnership PCOR Partnership	University of North Dakota, Energy & Environmental Research Center http://www.undeerc.org/pcor/	• Region rich in value-added geologic sequestration options • Wetlands a unique regional opportunity • Half-hour sequestration documentary aired on Prairie Public Television
MGSC	University of Illinois, Illinois State Geological Survey http://www.sequestration.org/	• Efforts centered on a CO_2 pipeline "fairway" and a focused region • Transportation plans highly developed • Link to agriculture interests through ethanol
MRCSP Midwest Regional Carbon Sequestration Partnership	Battelle Memorial Institute http://198.87.0.58/default.aspx	• Strong analysis and cost-supply curves for CO_2 sequestration • Region accounts for >20% of GHG emissions in the U.S. • Interactive website as outreach tool
Southeast Regional Carbon Sequestration Partnership	Southern States Energy Board http://www.secarbon.org/	• Electricity supply industry and governor-level participation • Carbon offset program, a web-based portal for advertising sequestration opportunities

C. Program Management

The DOE is dedicated to achieving the Sequestration Program goals and to utilizing the Program funds, shown in Figure 9, as effectively as possible. This is achieved through cooperative and collaborative relationships both domestically and internationally, competitive solicitations, analysis and project evaluation, project merit reviews and proactive public outreach and education. These activities support and enhance the R&D being conducted in the laboratory and the field. Following are management highlights.

Figure 9. DOE Sequestration Program Budget



Public/Private Partnerships Public-private partnerships and cost-shared R&D are a critical part of technology development for carbon sequestration. These relationships draw on pertinent capabilities that the coal, electricity supply, oil and gas, refining, and chemical industries have built up over decades and a technical knowledge base shared with the national laboratories, federal and state geological surveys, and academia. The program engages industry through competitive solicitations, which bring forward the companies and researchers with the best ideas and strongest capabilities and also challenges companies to offer significant cost-share, leveraging Federal dollars. In 2005, the program will award the second phase of the Regional Partnerships through an open competitive solicitation with 20% cost share required. Colleges and universities, private research institutes, national laboratories, and other federal and state agencies also play a significant role in technology development. Separate competitive solicitations are directed towards these institutions to spawn innovative, breakthrough concepts.

In-House R&D at NETL The **C**arbon **S**equestration **S**cience **F**ocus **A**rea (**CSSFA**) at NETL conducts science-based research and analysis in areas related to carbon sequestration using in-house facilities and resources at NETL. The CSSFA has been successful in fostering formal and information collaborative relationships with industry and academia in these high-risk research endeavors. The CSSFA also provides FE/NETL with a scientific understanding of the underlying technologies and, thus, enhances its effectiveness in implementing the carbon sequestration R&D portfolio.

Programmatic Environmental Impact Statement Many pilot and pre-commercial scale research activities are regulated under the National Environmental Policy Act (NEPA), a procedural regulation that requires environmental impact assessments of varying levels of rigor. NETL has conducted a review of the requirements under NEPA, and in October, 2003, Rita Bajura, then Director of NETL, issued a determination stating that "preparation of a programmatic environmental impact statement (PEIS) constitutes the appropriate level of environmental review for implementing the Sequestration Program."

In 2004 and 2005, FE/NETL hosted a series of public meetings where Federal Employees explained the goals and objectives of the Carbon Sequestration Program and the types of research projects the program was conducting and planned to conduct in the future. The PEIS will assess the environmental effects of current and potential future initiatives, including field tests, regional partnerships, and core R&D. Ultimately, it will help define the scope and direction of future Program activities. Later in 2005, FE/NETL will publish a draft Environmental Impact Statement and then conduct a second round of public meetings. More information on the FE/NETL PEIS can be found at: http://www.netl.doe.gov/sequestration

Interagency Coordination In each sequestration area, the DOE program collaborates with other agencies with overlapping responsibilities. For example, during 2003 and 2004 the DOE Carbon Sequestration Program collaborated with the National Academy of Sciences (NAS) in an effort to bolster R&D efforts in Breakthrough Concepts. A workshop hosted by DOE and NRC identified priorities for breakthrough research and a solicitation drawing from the research results produced a pool of over one hundred proposals. Seven awards were made in March 2004 and the work is proceeding.

International Collaboration The Carbon Sequestration Leadership Forum (CSLF) is an international initiative that is focused on development of improved cost-effective technologies for the separation and capture of carbon dioxide for its transport and long-term safe storage. The purpose of the CSLF is to make these technologies broadly available internationally; and to identify and address wider issues relating to carbon capture and storage. This could include promoting the appropriate technical, political, and regulatory environments for the development of such technology. In 2005 the CSLF welcomed France as a member and endorsed ten carbon sequestration projects around the world. Information on the CSLF and its activities can be found at http://www.cslforum.org

Charter CSLF Signing Ceremony, June 2003

The Carbon Sequestration Program achieves informal international collaborations that complement the CSLF through a variety of mechanisms, including formal bilateral and multilateral agreements, less formal cooperation agreements, and coordination of funding by different governments and the private sector. In 2005 the Sequestration Program provided technical assistance to the Intergovernmental Panel on Climate Change including review of a special report on CO_2 Capture and Geologic Storage and another on Carbon Accounting Protocols.

Systems, Economic, and Benefits Analyses Systems analyses and economic modeling of potential new processes are crucial to providing sound guidance to R&D efforts, which are investigating a wide range of CO_2 capture options. Many of the technologies being developed by the program are investigated at the laboratory or pilot scale. Systems analyses offer the opportunity to visualize how these new technologies might fit in a full-scale power plant and identify potential issues with their integration. Results of the analyses help make decisions on what technologies the Program should continue funding and how the research can be modified to help the technology succeed at full scale. Systems and economic analyses are performed by NETL analysts on the full range of technologies being developed through the Sequestration Program. Results of these studies are posted on the NETL Sequestration Website.

Systems analysis efforts are aided through the use of modeling tools. To enable the modeling of sequestration systems, NETL funds the development of the Integrated Environmental Control Model (IECM) which is a publicly-available model that now includes options for CO_2 capture and storage. http://www.iecm-online.com/

The Program conducts independent studies and participates in cross-cutting studies to model the future national energy situation. These activities include Program-specific analyses to look at how sequestration might help meet future CO_2 emissions reductions goals. They also include broader efforts that use large models like DOE's National Energy Modeling System (NEMs) or ICF's Integrated Planning Model (IPM) to address the benefits and roles of the full suite of advanced fossil energy technologies. The most recent programmatic benefits analysis can be downloaded at:
http://www.netl.doe.gov/coal/Carbon%20Sequestration/pubs/analysis/GHGT-7%20ID%20506%20Atmospheric%20Stabilization.pdf

Education and Outreach The notion of capturing and sequestering carbon dioxide and other greenhouse gases is relatively new, and many people are unaware of its role as a greenhouse gas reduction strategy. Increased education and awareness are needed to achieve acceptance of carbon sequestration by the general public, regulatory agencies, policy makers, and industry and, thus, enable future commercial deployments of advanced technology. The following activities highlight the Program's education and outreach efforts:

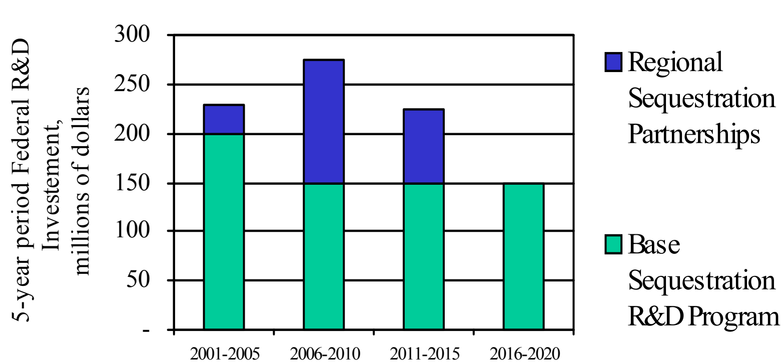
- Carbon Sequestration Webpage at the NETL site
- Monthly sequestration newsletter
- The Sequestration Technology Roadmap and Program Plan, revised annually
- The National Conference on Carbon Sequestration, held annually in the late spring in the Washington, DC, area
- Educational curriculum on global climate change and GHG emissions mitigation options

In addition, the program management team participates in technical conferences through presentations, panel discussions, breakout groups, and other formal and informal venues. These efforts expose professionals working in other fields to the technology challenges of sequestration and also enable examination of some of the more detailed issues underlying the technology.

In concert with R&D, the Program seeks to engage non-governmental organizations (NGO's) and federal, state, and local environmental regulators to raise awareness of the priority the Program places on evaluating the potential environmental impacts of sequestration and ensuring that selected technologies preserve human and ecosystem health. Many of the Program's R&D projects have their own outreach component. For example, field activities at the Mountaineer Power Plant and the Frio Brine Project have resulted in articles that have been run in newspapers across the country. Also, the Regional Partnerships will enhance technology development but also engage regulators, policy makers, and interested citizens at the state and local level through innovative outreach mechanisms. The Program works directly with non-governmental organizations and the environmental community through a variety of activities. Successful outreach entails two-way communications, and the Program will consider concerns voiced at outreach venues and continually assess the adequacy and focus of the current R&D portfolio.

Resource Requirements Figure 10 shows the estimated resources needed to pursue the opportunities identified in the Program plan and to achieve the Program's goals. The base Program funding is estimated at roughly $55 million per year. The Regional Partnerships require an initial investment but are structured to become self-sustaining by 2013.

Figure 10. Funding Requirements of the Carbon Sequestration Program



If you have any questions, comments, or would like more information about DOE's Carbon Sequestration Program, please contact the following persons:

Program-level Personnel:

National Energy Technology Laboratory Strategic Center for Coal Office of Fossil Energy	**U.S. Department of Energy Office of Coal and Power Systems Office of Fossil Energy**
SCOTT KLARA (412) 386-4864 Scott.Klara@netl.doe.gov	LOWELL MILLER (301) 903-9451 Lowell.Miller@hq.doe.gov
SEAN PLASYNSKI (412) 386-4867 Sean.Plasynski@netl.doe.gov	BOB KANE (202) 586-4753 Robert.Kane@hq.doe.gov
SARAH FORBES (304) 285-4670 Sarah.Forbes@netl.doe.gov	JAY BRAITSCH (202) 586-9682 Jay.Braitsch@hq.doe.gov

Technology Experts and Project Managers at the National Energy Technology Laboratory*:*

HEINO BECKERT (304) 285-4132 Heino.Beckert@netl.doe.gov	JOSE FIGUEROA (412) 386-4966 Jose.Figueroa@netl.doe.gov
CHARLIE BYRER (304) 285-4547 Charlie.Byrer@netl.doe.gov	TIMOTHY FOUT (304) 285-1341 Timothy.Fout@netl.doe.gov
DAWN CHAPMAN (304) 285-4133 Dawn.Chapman@netl.doe.gov	DAVID HYMAN (412) 386-6572 David.Hyman@netl.doe.gov
JARED CIFERNO (412) 386-5862 Jared.Ciferno@sa.netl.doe.gov	DAVID LANG (412) 386-4881 David.Lang@netl.doe.gov
KAREN COHEN (412) 386-6667 Karen.Cohen@netl.doe.gov	JOHN LITYNSKI (304) 285-1339 John.Litynski@netl.doe.gov

You can also find information about carbon sequestration at our web sites:

http://www.netl.doe.gov/sequestration
http://www.fe.doe.gov/coal_power/sequestration/

A REPRINT FROM

A REPRINT FROM THE December 2002 ISSUE OF

ENVIRONMENTAL PROGRESS

U.S. DOE Integrated Collaborative Technology Development Program for CO_2

Scott M. Klara and
Rameshwar D. Srivastava

U.S. DOE Integrated Collaborative Technology Development Program for CO_2 Separation and Capture

Scott M. Klara[a] and Rameshwar D. Srivastava[b]

[a] National Energy Technology Laboratory, United States Department of Energy, Pittsburgh, PA 15236

[b] Science Applications International Corporation, National Energy Technology Laboratory, Pittsburgh, PA 15236

Electric power generation represents one of the largest carbon dioxide (CO_2) emitters in the United States. Roughly one-third of all the United States' carbon emissions come from power plants. Since electricity generation is expected to grow, and fossil fuels will continue to be the dominant fuel source, power generation can be expected to provide even greater CO_2 contributions in the future. Consequently, an important component of the United States Department of Energy's (DOE's) research and development program is dedicated to reducing CO_2 emissions from power plants by developing technologies to capture CO_2 for utilization and/or sequestration. A primary goal of this research is to develop technology options that dramatically lower the cost of eliminating CO_2 from flue gas and other streams by use of either pre- or post-combustion processes. This research is in its early stages, and is exploring a wide range of approaches, including membranes, improved CO_2 sorbents, advanced scrubbing, oxyfuel combustors, formation of CO_2 hydrates, and economic assessments. This paper presents an overview of the DOE research program in the area of CO_2 separation and capture, while specifically addressing the status of research efforts related to promising pathways and potential technological breakthroughs.

INTRODUCTION

Fossil fuels currently supply over 85% of the energy needs of the U.S., and their combustion is responsible for about 90% of the greenhouse gas (GHG) emissions in the U.S. [1]. Use of these fuels, domestically and internationally, is expected to increase well into the 21st century. The Energy Information Administration within the U.S. Department of Energy (DOE) projects U.S. consumption of coal, oil, and natural gas to increase by 40%, and carbon emissions to rise by 33% over the next 20 years (See Figure 1).

Carbon sequestration holds great potential to reduce GHG emissions at costs and impacts that are economically and environmentally acceptable. The DOE's Office of Fossil Energy's (FE) formal carbon sequestration effort began in 1997.

The Carbon Sequestration Program is pursuing five technology pathways to reduce GHG emissions:

- Separation and capture
- Geologic sequestration
- Terrestrial sequestration
- Oceanic sequestration
- Novel sequestration systems

These five pathways encompass a broad set of opportunities for both technology development and partnership formation for national and international cooperation. This paper deals mainly with the first of these pathways, namely separation and capture.

In addition to CO_2, methane (CH_4) and nitrous oxide (N_2O) are other major anthropogenic emissions that contribute to global climate change. On a pound for pound basis, both CH_4 and N_2O are more potent GHGs than CO_2. However, in terms of the quantity emitted, CO_2 far outstrips other GHGs and is, thus, the primary focus of mitigation efforts. Efforts to decrease non-CO_2 GHG emissions are included in the Sequestration Program, but are not discussed in this paper.

An important component of DOE's Carbon Sequestration program is directed toward reducing CO_2 emissions from power plants. Roughly one-third of the United States' anthropogenic CO_2 emissions come from power plants (See Figure 2). CO_2 emissions in the U.S. from electricity generation by fossil-fuel burning power plants increased by 23.5% between 1990 and 2000 [2]. Moreover, most power plants use air for combustion, which means that the major constituent of the flue gas is nitrogen. This makes it difficult and expensive to capture CO_2 as a concentrated stream, which is required for most storage, conversion, and reuse applications. One way of mitigating GHG emissions in a safe and environmentally-friendly manner is to capture CO_2 and store it in geological formations.

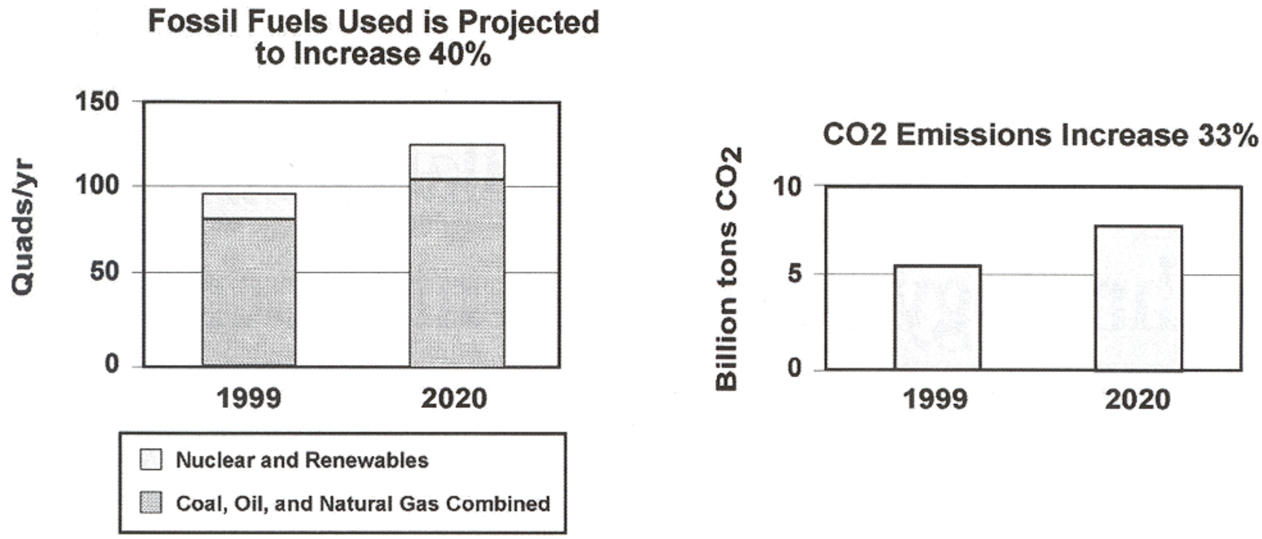


Figure 1. U.S. energy consumption and GHG emissions in 2020.

This has emerged as one of the most promising options for sequestering CO_2 from energy plants [3].

Carbon sequestration is an underexplored area of science and technology. In order for recovery/sequestration to work, improved CO_2 capture technologies are needed, and costs must be reduced substantially. Capture technology, based on the use of physical or chemical sorbents, such as amines, is in wide use today to remove CO_2 from natural gas, which can be used in the food industry and for tertiary recovery in oil fields. However, the cost is on the order of $50 per ton of CO_2 removed, or about 5 cents per kWh, too high for cost-effective GHG emissions reductions. Additionally, existing capture systems use substantial amounts of energy, reducing a power plant's net generation capacity, sometimes by as much as 30%. DOE's long-term goal is to achieve sequestration with only a modest increase in energy costs [4, 5]. The programmatic timeline is to demonstrate, at commercial scale, a portfolio of safe and cost-effective GHG capture, storage, and mitigation technologies by 2012.

CARBON SEQUESTRATION RESEARCH AND DEVELOPMENT PROGRAM

Before it can be sequestered, CO_2 must first be separated and captured. Therefore, the Carbon Sequestration Research and Development Program is exploring a portfolio of new and improved technologies to reduce the capital cost and energy penalty for CO_2 capture. During the FY2000 to FY2002 period, the DOE Carbon Sequestration Program issued a solicitation and selected 20 R&D projects in the areas of CO_2 capture and storage in geologic formations. These programs have up to a 40% non-DOE cost share. This research is in its early stages and is exploring a wide range of capture approaches, including membranes, improved CO_2 sorbents, advanced combustor concepts, advanced scrubbing, formation of CO_2 hydrates, and economic assessments. DOE is also a partner in the CO_2 Capture Project (CCP) with an international team of energy companies to develop a set of new technologies to reduce the cost of capturing CO_2 from fossil fuel combustion.

There are two general approaches to CO_2 capture: precombustion decarbonization and post-combustion capture. Either the carbon can be removed before the fuel is burned, or CO_2 can be recovered from the flue gas. In addition, the use of pure oxygen, rather than air, in combustion, known as oxyfuel combustion, has a high potential for reducing CO_2 separation and capture costs.

PRECOMBUSTION DECARBONIZATION

Precombustion decarbonization involves removal of carbon from a gaseous, liquid, or solid fuel before it is burned. Various approaches are possible. A very promising technology involves gasifying coal and then scrubbing the CO_2 from the fuel gas before combustion. The CO_2 is normally removed by a chemical or physical absorption system. Existing capture technologies operate at a low temperature, requiring the syngas produced in the gasifier to be cooled for CO_2 capture and then reheated before combustion in a turbine. Substantial cost reductions in CO_2 capture and separation are expected to come through integrated designs incorporating the use of membranes and other breakthrough recovery technologies.

CO_2 Selective Ceramic Membrane to Improve the Water-Gas Shift Reaction

This technology involves precombustion decarbonization with the addition of an innovative water-gas shift (WGS) reactor to increase the amount of CO_2 captured. The WGS reactor consists of ceramic tubes that incorporate a membrane permeable to CO_2, but not to other gases. The tubes are filled with catalyst. As the fuel gas from the coal gasifier passes through the WGS reactor, the CO_2 produced by the reaction, as shown in Equation 1, diffuses through the membrane, allowing the reaction to approach completion.

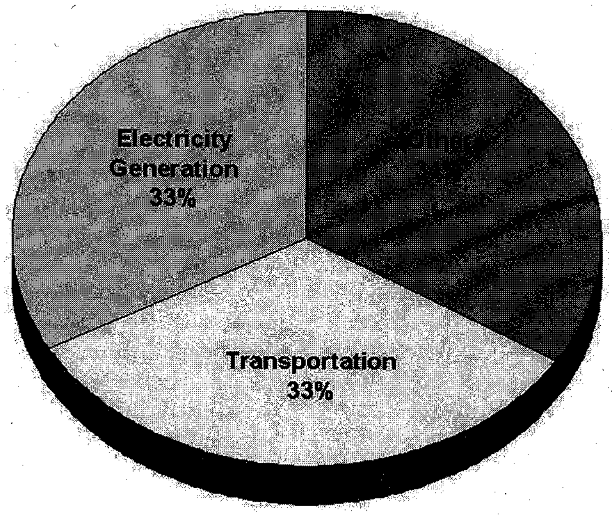


Figure 2. U.S. carbon emissions sources.

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad (1)$$

This produces a hydrogen-rich fuel stream, while simultaneously producing a pure CO_2 stream for use or sequestration. The hydrogen can be sent to a fuel cell or burned in a combustion turbine. In either case, the only product is water, which is innocuous to the environment. This project is being conducted by Media and Process Technology, Inc., in partnership with the University of Southern California. They have developed a technique for depositing hydrotalcite in the pores of a ceramic substrate. The hydrotalcite is permeable to CO_2, but plugs the pores, preventing passage of other gases. The project team is currently working on improving production procedures and determining operating conditions to maximize CO_2 permeance.

POST-COMBUSTION CO_2 CAPTURE

Post-combustion capture involves the removal of CO_2 from the flue gas produced by fuel combustion. The major problem with this approach is that flue gas is usually at near atmospheric pressure, and the CO_2 concentration is low. The resulting low partial pressure of CO_2 results in only a small driving force for traditional adsorption/absorption processes. While post-combustion CO_2 capture may not have the greatest potential for step-change reductions in separation and capture costs, it has the greatest near-term potential for reducing emissions, since post-combustion processes can be retrofitted to existing facilities. Although the processes discussed below can be used to remove CO_2 from flue gas, the benefits of these developments will be equally applicable to the removal of carbon dioxide from gasifier product streams for the production of syngas or pure hydrogen.

Electric Swing Adsorption

Electric Swing Adsorption (ESA) is an advanced separation system for CO_2 removal from syngas being developed for use with the gasification of low hydrogen-to-carbon ratio fuels, such as petroleum coke. Oak Ridge National Laboratory has developed a novel process, which adsorbs CO_2 on a carbon substrate. After saturation of the carbon fiber adsorbent with CO_2, immediate desorption of the adsorbed gas is accomplished by applying low voltage across the adsorbent. This technology is being developed to remove CO_2 from the exhaust gas of a conventional turbine combined with a non-condensing steam turbine. Calculations based on available adsorption data indicate that it should be possible to develop an improved CO_2-separation process compared to existing technology.

Stable High Temperature Polymer Membranes

Many membrane systems used for industrial gas separation applications employ polymer membranes. Such applications include the production of high-purity nitrogen, dehydration and removal of acid gases from natural gas, and recovery of hydrogen from process streams. However, many gas separation applications require materials that are stable at high temperatures and pressures. Polymeric materials currently used commercially have thermal and mechanical limits too low for such applications. Consequently, there is a compelling need for membrane materials that can operate under more extreme conditions for extended periods of time while providing an acceptable level of performance.

Los Alamos National Laboratory is developing a high-temperature polymeric membrane with better separation performance by supporting a polybenzimidazole (PBI) film on a sintered metal support. PBI possesses excellent chemical resistance, a high glass transition temperature (450° C), and good mechanical strength. Tests for H_2, CO_2, CH_4, and N_2 permeability with the membrane oriented with the polymeric layer on the feed side have shown promising results. This type of membrane is highly selective and able to operate at flue gas conditions.

Advanced Gas/Liquid Scrubbing

A major problem associated with chemical absorption using amines is the degradation of the solvent through irreversible side reactions with SO_2 and other flue gas components. Such reactions lead to numerous problems, such as foaming, fouling, increased viscosity, and formation of stable salts in the amine. Amine degradation results in solvent loss, requiring a replacement rate of up to eight pounds of amine per ton of CO_2 captured. A focus of R&D activities at the National Energy Technology Laboratory (NETL) is a study of amine degradation under actual plant conditions.

This study will lead to a better understanding of the chemistry of solvent degradation, which is known to increase corrosion. Understanding this phenomenon will improve operations and decrease costs, since to reduce corrosion, solvent strength is kept relatively low, resulting in large equipment sizes and high regeneration energy requirements. In addition, several researchers have shown that blending amines increases the absorption rate. The work at the University of Texas at Austin focuses on expanding the investigation of promoted potassium carbonate using piperazine as the amine.

Regenerable CO_2 Sorbent Development

A different approach for CO_2 capture employs dry scrubbing—a process that involves chemical adsorption with a dry sorbent. Such a sorbent can remove the pollutant, be regenerated to produce a concentrated stream of CO_2, and be recycled. This process can have economic advantages compared to commercially available wet scrubbing amine processes.

Research Triangle Institute has initiated development of a process that uses a regenerable, sodium-based sorbent for CO_2 recovery. Preliminary microreactor tests with sodium carbonate have indicated that absorbing CO_2 and steam to form bicarbonate, with subsequent regeneration to the carbonate, is a viable process. Because sorbent regeneration uses waste heat, the power requirement for capture of CO_2 is relatively small. Various system configurations are being simulated to define optimal heat management.

NETL has pioneered research to identify regenerable sorbents that can be used for CO_2 capture. The active component in a calcium-based sorbent being studied chemically bonds with CO_2 and is later regenerated using heat or a reducing agent. Packed bed testing is now in the planning stage. In another project, CO_2 is absorbed by a zeolite based sorbent, and a temperature/pressure swing is performed to recover the carbon dioxide. The project team (NETL and Carnegie-Mellon University) is currently working on simulation modeling to understand the performance of high-temperature sorbents and on high-pressure reactor testing of promising synthetic zeolites.

OXYFUEL TECHNOLOGY

Oxygen-Fired Combustion for CO_2 Capture

The objective of oxygen-fired combustion is to burn the fuel in enriched air or pure oxygen to produce a concentrated stream of CO_2. Oxygen-fired combustion presents significant challenges, but also provides a high potential for a technological breakthrough and a step-change reduction in CO_2 separation and capture costs. The barriers and issues include:

- Oxygen from cryogenic air separation is expensive and, because in oxygen-fired combustion, all the carbon in the fuel is converted to CO_2 using pure oxygen, rather than only part of the carbon with gasification, oxygen combustion consumes several times more oxygen than coal gasification followed by combustion of the syngas in air.
- Combustion of fuels in pure oxygen occurs at a temperature too high for existing boiler or turbine materials, while CO_2 recycle to control temperature increases the parasitic power load.

Development and costing of an optimized oxygen-fired combustion scheme requires an engineering study to identify and resolve the technical issues related to application of oxygen firing with flue gas recycle to the boiler and process heaters. Alstom Power has outlined an approach in which two sets of economic evaluations would analyze a fossil fuel-based (coal and petroleum coke) circulating fluidized bed (CFB) combustor, and a biomass-based CFB for power production. The first step is to identify and analyze normal baseline conditions for CFB combustion with air firing both without CO_2 capture and with a novel high-temperature CO_2 capture and sorbent regeneration process. Next, CFB-based power plants employing an oxygen/recycled flue gas mixture as the oxidizing agent will be studied to determine what operating conditions and gas cleanup processes are most economical. The CO_2 concentration in the flue gas can be greatly increased by using oxygen instead of air for combustion. Flue gas is recycled to moderate the combustion temperature.

Comparisons will also be made with Integrated Gasification Combined Cycle (IGCC) cases that have already been evaluated by Parsons Energy and Chemical Group. In this way, important features that can improve plant operations by utilizing oxygen firing will be explored, identified, and included in plant designs.

Integration of Membrane Air Separation

The economics of both oxygen-firing and IGCC can be improved by the application of advanced oxygen production technology. New air separation processes using high temperature oxygen ion transport ceramic membranes are being developed by several consortia. For oxygen-fired combustion applications, integration of an oxygen transport membrane (OTM) for oxygen production with the combustion system can provide a method for the cost-effective capture of CO_2 from power plants. Praxair, in conjunction with Alstom Power, has initiated the development of a novel technology that integrates a high-temperature OTM with boiler components to enhance both oxygen production and boiler efficiency (See Figure 3).

OTM membranes are based, in part, on Praxair-patented materials that have demonstrated ability for rapid electron conduction. A condensing heat exchanger will be used to take advantage of the high water content in the flue gas from combustion with pure oxygen. A high driving force across the ceramic membrane, due to pressurized air, and the high temperature environment inherent in combustion, result in a significant reduction in the power consumption for oxygen production. The resultant combustion process will not only lead to low NO_x and CO emissions, but also increase the CO_2 concentration in the flue gas sent to the capture system, thus leading to lower capital costs. The technical challenge is to develop materials with enhanced conductivity and stability, and to produce ceramic structures specifically suited to combustion applications.

NOVEL CONCEPTS

Carbon Dioxide Separation Using Hydrates

An entirely new concept for recovering CO_2 from process streams is the formation of hydrates, ice-like

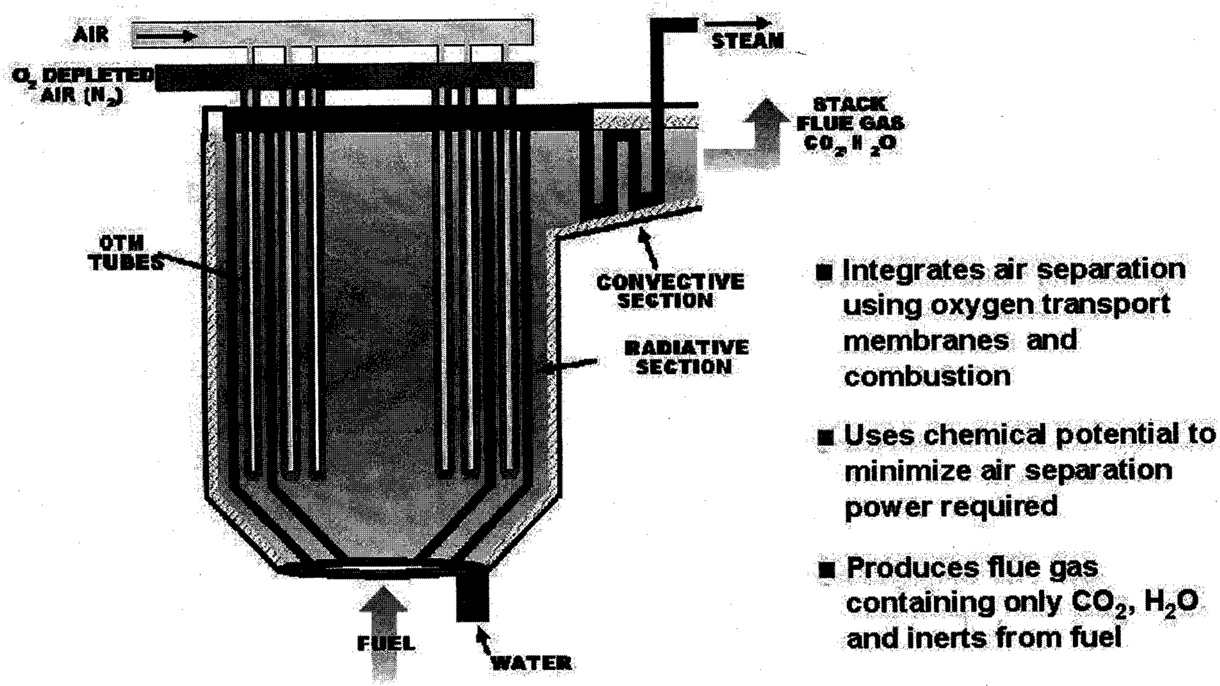


Figure 3. Praxair advanced boiler.

complexes of water and CO_2 molecules. Many people are familiar with methane hydrates, in which a methane molecule is enclosed in a cage of water molecules, but are unaware that CO_2 can form similar hydrates under suitable conditions. The California Institute of Technology has developed a bench-scale apparatus to produce CO_2 hydrates. The objective of the current project team (Los Alamos National Laboratory, Nextant, Inc., and SIMTECHE) is to develop this concept into the basis for a commercial process that removes CO_2 from flue gas by contacting it with water at low temperature (0° C) and high pressure (1-7 MPa) to form crystalline ice-like solids that can be removed from the system.

A new test unit has been constructed for experimentation. Figure 4 is a schematic of a CO_2 hydrate separation process operating on a synthesis gas stream that has undergone the WGS reaction. Water and CO_2 in a greater than 12/1 molar ratio flow through a venturi to achieve intimate contact, and then into a cooler to remove the heat of formation of the hydrate. The slurry and unreacted gas then flow to a separator. Work to date has demonstrated that hydrates can be formed in systems with very short residence times, and that continuous operation is possible, provided operating conditions are adjusted so that plugging does not occur.

The next step in the development process is the design, construction, and operation of a pilot plant. However, further data are needed before this can be done, including the physical properties of the hydrate slurry, practical ranges of the key process variables, and tests with $CO_2/H_2/H_2S$ mixtures. Using CO_2 hydrates to purify gas streams is a potentially less energy-intensive recovery method. It is also possible that CO_2 hydrate slurries could be pumped to sequestration sites without regeneration. Implementation of this technology will be best suited to gasification systems that operate at pressures higher than those of typical flue gas streams.

Chemical Looping

Indirect combustion of coal, sometimes referred to as chemical looping, will be evaluated by Alstom Power. In chemical looping, oxygen for combustion is provided by a metal oxide, rather than by air. Fuel gas (CO plus H_2) produced by the gasification of coal reduces a solid transition metal oxide in a fluidized bed reactor to a lower oxidation state, producing water and CO_2. The off-gas stream is cooled to condense water and produce a pure CO_2 stream for sequestration. The reduced metal containing solid is transferred to a second fluidized bed reactor, where it is reoxidized with air. This exothermic reaction heats the oxygen-depleted air, which is sent to power production.

OTHER ACTIVITIES

Modeling/Assessment

There is a need to develop a comprehensive economic model that that will enable different options for CO_2 capture from power plants to be systematically evaluated, including pipeline costs. Carnegie Mellon University is developing such a model. The initial focus includes current commercial technologies, such as amine-based CO_2 capture, shift conversion, pipelines, and geologic storage. The model is expected to be capable of establishing a common

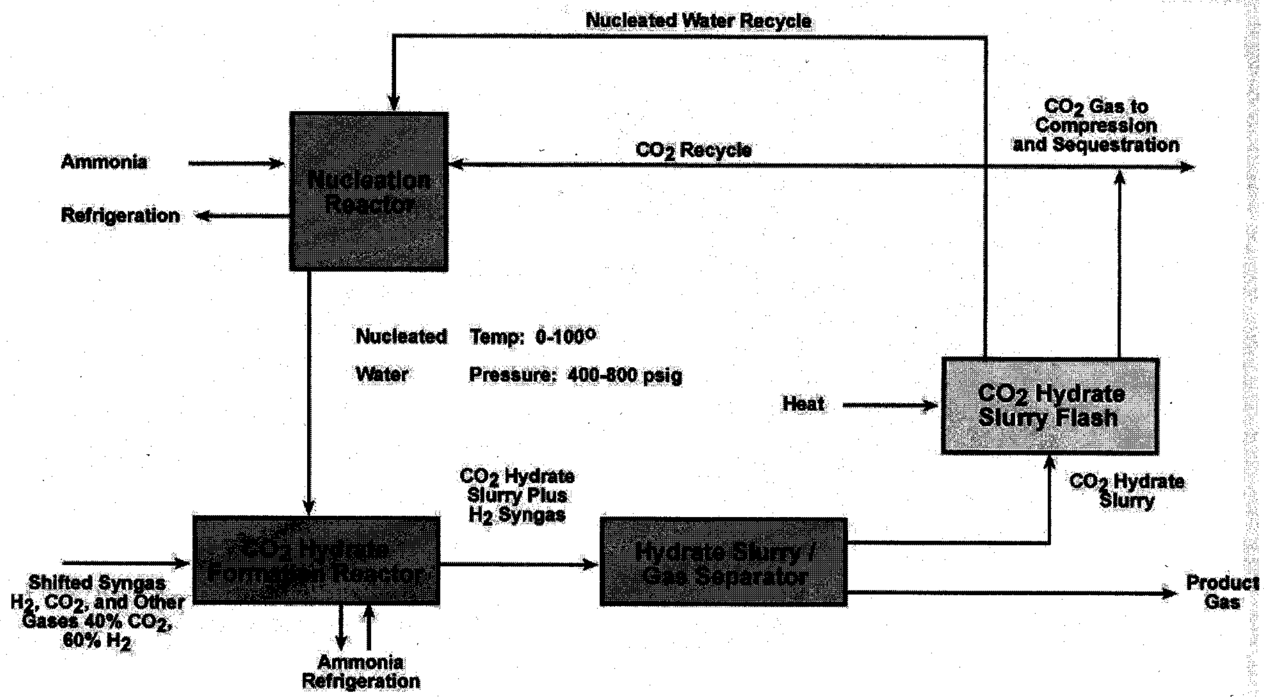


Figure 4. Conceptual process block flow diagram of a CO_2 hydrate process.

set of performance metrics and evaluating the overall cost of CO_2 sequestration, including the component costs of new separation and capture modules, transportation and sequestration in geologic reservoirs and unmineable coal seams, and use in enhanced oil recovery.

NETL and Science Applications International Corporation are developing a computer model-based technique for evaluating CO_2 recovery and sequestration technologies. With existing studies as a baseline, all technologies in the DOE portfolio will be evaluated to continually assess their potential technical and economic performance. This will ensure that the highest potential projects are kept at the forefront of the DOE development effort.

CO_2 Capture Project

To further enhance the effort to reduce GHG emissions, DOE is sponsoring the CO_2 Capture Project (CCP) with an international team of energy companies lead by BP, and including Chevron-Texaco, ENI (Italy), Shell, Norsk Hydro (Norway), PanCanadian (Canada), Statoil (Norway), and Suncor Energy (Canada). This joint industry project will demonstrate the feasibility of capturing the CO_2 produced from burning a variety of fuel types and storing it in unmineable coal seams and saline aquifers.

The CCP has issued contracts with technology developers in the U.S., the European Union, and Norway to carry out studies in various process areas, including geologic storage, post-combustion CO_2 separation and capture, precombustion decarbonization, and fuel combustion with pure oxygen [6]. The potential exists for many scientific breakthroughs from this project, such as the development and evaluation of a combined shift reaction and CO_2 separation system employing high temperature adsorbents. This process would selectively remove CO_2 from a reacting gas mixture, thereby increasing conversion and providing two gas streams requiring minimal further purification. Technology developed by Air Products and Chemicals involves the precombustion decarbonization of a hydrocarbon feedstock that has been gasified by reaction with steam and/or oxygen to produce a $H_2/CO_2/H_2O/CO$ gas mixture with trace contaminants. This concept has already been demonstrated at laboratory scale. Development needs are to apply the system to CO_2 capture and optimize the adsorbent and cycle for large-scale use.

Four membranes have been identified to achieve the CO_2 recovery target at a concentration above 97 mol %. Each of these membranes (Cu-Pd, supported zeolite, silica, and electro-ceramic) will be developed and characterized. For example, ECN Dutch Energy Efficiency Institute will develop silica membranes and provide mathematical models. Fluor Daniels will develop simulations of the overall process incorporating a model of the membrane reactor supplied by ECN.

Other potential scientific breakthroughs that could result from the CCP include:

- New solvents and/or contactors to reduce the cost of CO_2 separation.
- An emerging H_2 generation process integrated with CO_2 capture.
- Understanding the production of fuel-grade H_2 and its combustion properties.

- An enhanced understanding of controls and requirements for geologically sequestering CO_2.

Information on capture and sequestration options generated during the performance of these parallel and complimentary studies will maximize technology transfer and, hence, benefit CO_2 reduction efforts in the U.S and globally.

CONCLUSIONS

The DOE Carbon Sequestration Program is developing a portfolio of technologies that hold great potential to reduce GHG emissions. The programmatic timeline is to demonstrate a series of safe and cost effective GHG capture, storage and mitigation technologies at the commercial scale by 2012, with deployment leading to substantial market penetration beyond 2012. Developments are directed toward substantial improvements in performance and cost reduction compared to state-of-the-art alternatives. Wide deployment of these technologies holds great promise to slow the growth of GHG emissions in the near-term, while ultimately leading to stabilized emissions towards the middle of the 21st century.

This paper has presented a brief overview of the DOE Carbon Sequestration Program. More details on these and other R&D projects in the portfolio can be found at the referenced Web site [5].

LITERATURE CITED

1. U.S. DOE and U.S. Environmental Protection Agency, "Carbon Dioxide Emissions from the Generation of Electric Power in the United States," Washington, DC, October 15, 1999, available at http://www.epa.gov.
2. U.S. DOE, "International Energy Outlook 2001," DOE/EIA-0484, Energy Information Administration, Washington, DC, 2001.
3. **Herzog, H., E. Drake, and E. Adams**, "CO_2 Capture, Reuse, and Storage Technologies for Mitigating Global Climate Change—A White Paper," U.S. DOE/DE-AF22-96PC01257, Washington, DC, January 1997.
4. **Schmidt, C.E., S. Klara, and R.D. Srivastava**,"DOE Carbon Sequestration Program," U.S. Department of Energy, Proceedings of the EUEC 2002, Tucson, AZ, 2002.
5. http://www.netl.doe.gov/coalpower/sequestration, August 2002.
6. **Hill, G.**, http://www.co2captureproject.org, December 2001.

PERGAMON

Energy Conversion and Management 44 (2003) 2699–2712

ENERGY CONVERSION & MANAGEMENT

www.elsevier.com/locate/enconman

Integrated collaborative technology development program for CO_2 sequestration in geologic formations—United States Department of Energy R&D

Scott M. Klara [a,*], Rameshwar D. Srivastava [b], Howard G. McIlvried [b]

[a] National Energy Technology Laboratory, United States Department of Energy, Pittsburgh, PA 15236, USA

[b] Science Applications International Corporation, National Energy Technology Laboratory, Pittsburgh, PA 15236, USA

Received 10 October 2002; accepted 28 January 2003

Abstract

A major contributor to increased atmospheric CO_2 levels is fossil fuel combustion. Roughly one third of the carbon emissions in the United States comes from power plants. Since electric generation is expected to grow and fossil fuels will continue to be the dominant fuel source, there is growing recognition that the energy industry can be part of the solution to reducing greenhouse gas emissions by capturing and permanently sequestering CO_2. Consequently, an important component of the United States Department of Energy's (DOE) research and development program is dedicated to reducing CO_2 emissions from power plants by developing technologies for capturing CO_2 and for subsequent utilization and/or sequestration.

Injection of CO_2 into geologic formations is being practiced today by the petroleum industry for enhanced oil recovery, but it is not yet possible to predict with confidence storage volumes, formation integrity and permanence over long time periods. Many important issues dealing with geologic storage, monitoring and verification of fluids (including CO_2) in underground oil and gas reservoirs, coal beds and saline formations must be addressed. Field demonstrations are needed to confirm practical considerations, such as economics, safety, stability, permanence and public acceptance.

This paper presents an overview of DOE's research program in the area of CO_2 sequestration and storage in geologic formations and specifically addresses the status of new knowledge, improved tools and enhanced technology for cost optimization, monitoring, modeling and capacity estimation. This paper also highlights those fundamental and applied studies, including field tests, sponsored by DOE that are measuring the degree to which CO_2 can be injected and remain safely and permanently sequestered in geologic formations while concurrently assuring no adverse long term ecological impacts.
Published by Elsevier Science Ltd.

Keywords: Carbon dioxide sequestration; Geological media; Sedimentary basins

* Corresponding author. Tel.: +1-412-386-4864; fax: +1-412-386-4604.
E-mail address: scott.klara@netl.doe.gov (S.M. Klara).

0196-8904/03/$ - see front matter Published by Elsevier Science Ltd.
doi:10.1016/S0196-8904(03)00042-6

1. Introduction

Predictions of global energy use in this century suggest a continued increase in carbon emissions and rising concentrations of CO_2 in the atmosphere. A major contributor to increased greenhouse gas (GHG) emission levels is fossil fuel combustion. Roughly one third of the carbon emissions in the United States comes from power plants. Since electric generation is expected to grow and fossil fuels will continue to be the dominant fuel source, there is growing recognition that the energy industry can be part of the solution to reducing GHG emissions by capturing and permanently sequestering CO_2. Carbon sequestration holds great potential to reduce GHG emissions at costs and impacts that are economically and environmentally acceptable. The year 1997 represents the start of DOE's Office of Fossil Energy's (FE) formal Carbon Sequestration Program. The objective of the Carbon Sequestration Program is to provide long range options for drastically reducing CO_2 emissions from fossil fuel fired heat and power facilities [1,2].

The Carbon Sequestration Program is pursuing five technology pathways to reduce GHG emissions:

- Separation and Capture targets novel, low cost approaches for capture of carbon or CO_2 from energy production and conversion systems.
- Geologic Sequestration assesses the applicability and effectiveness of long term CO_2 storage in geological structures, such as oil and gas reservoirs, unmineable coal seams and deep saline aquifers.
- Terrestrial Sequestration examines the potential to enhance terrestrial uptake and retention of atmospheric CO_2 by coupling improved agricultural and forestry practices with fossil energy production and use systems.
- Oceanic Sequestration examines potential mechanisms for enhancing ocean uptake of atmospheric CO_2 or for deep ocean storage of liquid CO_2.
- Novel Sequestration Systems examines novel approaches to chemical, biological or other processes to recycle or reuse CO_2 produced by energy systems.

These five pathways encompass a broad set of opportunities for both technology development and partnership formation for national and international cooperation. A paper discussing the first of these pathways, separation and capture, was recently published [3]. This paper deals mainly with the second of these pathways, geologic sequestration. Summaries of technology developments emerging from the Carbon Sequestration Program are presented.

2. Sequestration of carbon dioxide in geologic formations

Geologic CO_2 sequestration involves the injection of CO_2 into geologic formations, the most important of which are deep coal seams, saline aquifers and depleted oil and gas reservoirs. The estimated capacity of geologic formations (see Fig. 1) is large enough to store decades to centuries worth of emissions. These capacity estimates are likely to be conservative, as the CO_2 seques-

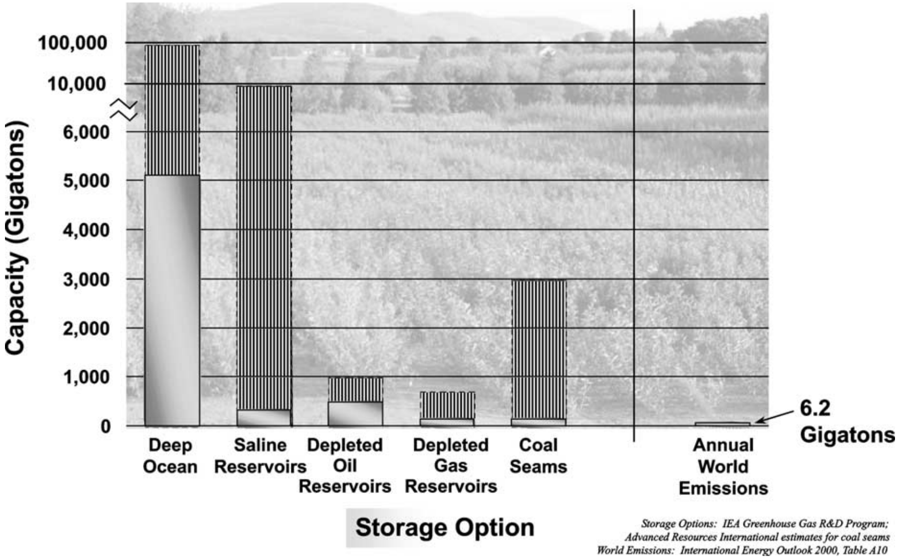


Fig. 1. Large potential worldwide storage capacity.

tration potential of geologic reservoirs depends on many factors that are, as yet, poorly understood. These include reservoir integrity, volume, porosity, permeability and pressure. Because these factors vary widely, even within the same reservoir, it can be difficult to establish a reservoir's storage potential with certainty.

Injection of CO_2 into geologic formations is being practiced today by the petroleum industry for enhanced oil recovery (EOR), but it is not yet possible to predict with confidence storage volumes, formation integrity and permanence over long time periods. Many important issues dealing with geologic storage, such as interactions between CO_2 and reservoir rock and other fluids and monitoring and verification of fluids (including CO_2) in underground oil and gas reservoirs, coal beds and saline formations, must be addressed.

Large scale field demonstrations are needed to confirm practical considerations, such as economics, safety, stability, permanence and public acceptance. Early tests will involve sequestration experiments in which collateral benefits are likely, such as storing CO_2 in depleted oil and gas reservoirs where additional hydrocarbons may be produced and sequestering CO_2 in coal seams in conjunction with coal bed methane (CBM) production. The main driver, however, is to ensure the safety of, and gain public acceptance for, large scale CO_2 sequestration projects. The purpose of DOE sponsored research in geologic sequestration is to provide answers to the many remaining questions.

The three major research thrusts of the geologic sequestration activity are:

- monitoring and verification;
- health, safety and environmental risk assessment;
- knowledge base and technology for CO_2 storage reservoirs.

3. Monitoring and verification

A critical R&D need is to develop a comprehensive monitoring and modeling capability that not only focuses on technical issues but also can help ensure that geologic sequestration of CO_2 is safe. Long term geologic storage issues, such as leakage of CO_2 through old well bores, faults, seals, or diffusion out of the formation, need to be addressed. Many tools exist or are being developed for monitoring geologic sequestration of CO_2, including well testing and pressure monitoring; tracers and chemical sampling; surface and bore hole seismic; and electromagnetic/geomechanical meters, such as tiltmeters. However, the spatial and temporal resolution of these methods may not be sufficient for performance confirmation and leak detection. Therefore, further monitoring needs include:

- high resolution mapping techniques for tracking migration of sequestered CO_2;
- deformation and microseismicity monitoring;
- remote sensing for CO_2 leaks and land surface deformation.

Fig. 2 provides an overview of the participants, approach and synergies for monitoring and verification projects within the DOE program. Following are descriptions of major projects aimed at developing effective monitoring tools and technologies, which hold high potential for improving our ability to characterize the location, quantity and condition of sequestered CO_2.

Sandia National Laboratory, Los Alamos National Laboratory, and the National Energy Technology Laboratory have partnered with an independent producer, Strata Production Company, to investigate down hole injection of CO_2 into a depleted oil reservoir, the West Pearl Queen Field, in New Mexico. A comprehensive suite of computer simulations, laboratory tests, field measurements and monitoring efforts will be used to understand, predict and monitor the geomechanical and hydrogeologic processes involved. Injection into this reservoir is planned through an inactive well, while a producing well and two shutoff wells will be used for monitoring. CO_2 migration and surface detection studies will be conducted by combining satellite visible light and infrared views with satellite radar and optical aerial photography. Remote geophysical surveys will attempt to detect and characterize changes in fluid saturation and pressure by observing the seismic response of the reservoir during injection. These observations will be used to calibrate, modify and validate modeling and simulation tools.

Use of new reservoir mapping and predictive tools (surface seismic and tracer injection) to develop a better understanding of the behavior of CO_2 in a geologic formation in conjunction with the Weyburn unit is being addressed by Natural Resources Canada and Dakota Gasification Company. Weyburn Field, in southwestern Saskatchewan, Canada, was discovered in 1954. Starting in 2001, several thousand tons per day of CO_2 are being pumped into this reservoir to produce incremental oil. The CO_2 is being transported by pipeline 330 km from the Great Plains Synfuels Plant in Beulah, North Dakota. It is expected that $\approx$50% of the CO_2 will remain sequestered with the oil that remains in the ground. The 50% that comes to the surface with the produced oil will come out of solution as the pressure drops and be recycled to the injection wells. This work will examine the way CO_2 moves through the reservoir rocks, the precise quantity that can be stored in a reservoir and how long the CO_2 could be expected to remain trapped in the underground formation.

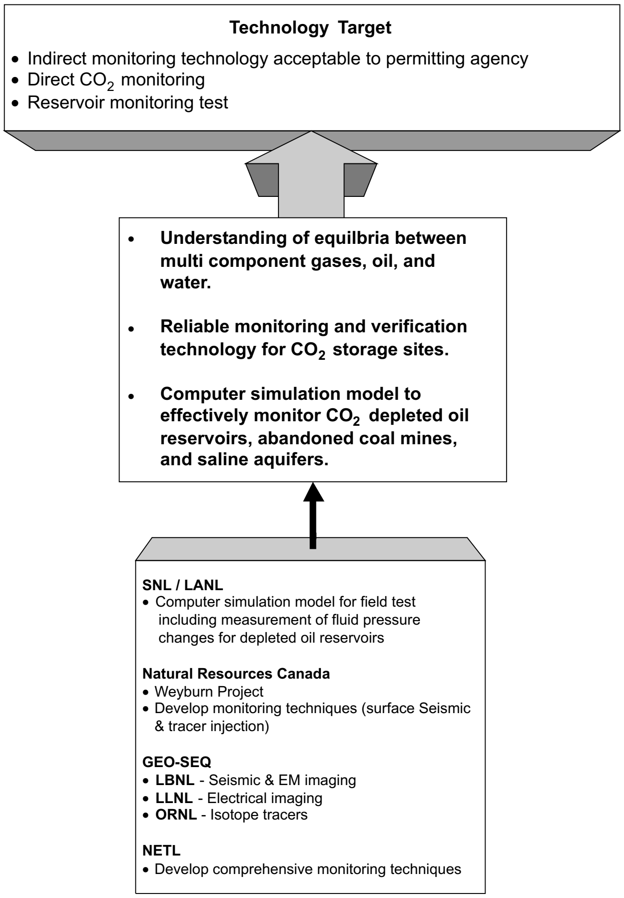


Fig. 2. Monitoring and verification.

Lawrence Berkley, Lawrence Livermore and Oak Ridge National Laboratories and their partners are developing innovative monitoring technologies to track migration of CO_2. Called GEO-SEQ, described later in conjunction with other major activities, the project will develop and use seismic techniques, electrical imaging and isotope tracers for optimizing value added sequestration technologies for brine, oil and gas and coal bed methane formations.

4. Health, safety and environmental risk assessment

Assessing the risks of CO_2 release from geologic storage sites is fundamentally different from assessing risks associated with hazardous materials, for which best practice manuals are often available. Because CO_2 is benign at low concentrations, a new framework for assessment, implementation and regulation will be needed.

Health, safety and environmental risk assessment is a process for identifying adverse health, safety and environmental consequences and their associated probabilities. The assessment of the risks associated with sequestration of CO_2 in geologic formations includes identifying potential subsurface leakage modes, likelihood of an actual leak, leak rate over time and long term implications for safe sequestration. Diagnostic options need to be developed for assessing leakage potential on a quantitative basis. Fig. 3 provides an overview of project participants, their approach, technology targets and the synergies involved in the DOE program.

Advanced Resources International is evaluating the effect of slow or rapid CO_2 leakage on the environment during initial operations or the subsequent storage period. The study will include a comprehensive and multi-disciplinary assessment of the geologic, engineering and safety aspects of natural analogs. Five large natural CO_2 fields, which provide a total 1.5 billion ft^3/day of CO_2 for EOR projects in the United States, have been selected for evaluation [4]. Based on the results of a geochemical analysis of CO_2 impacts and geomechanical modeling, an evaluation of environmental and safety related factors will be made.

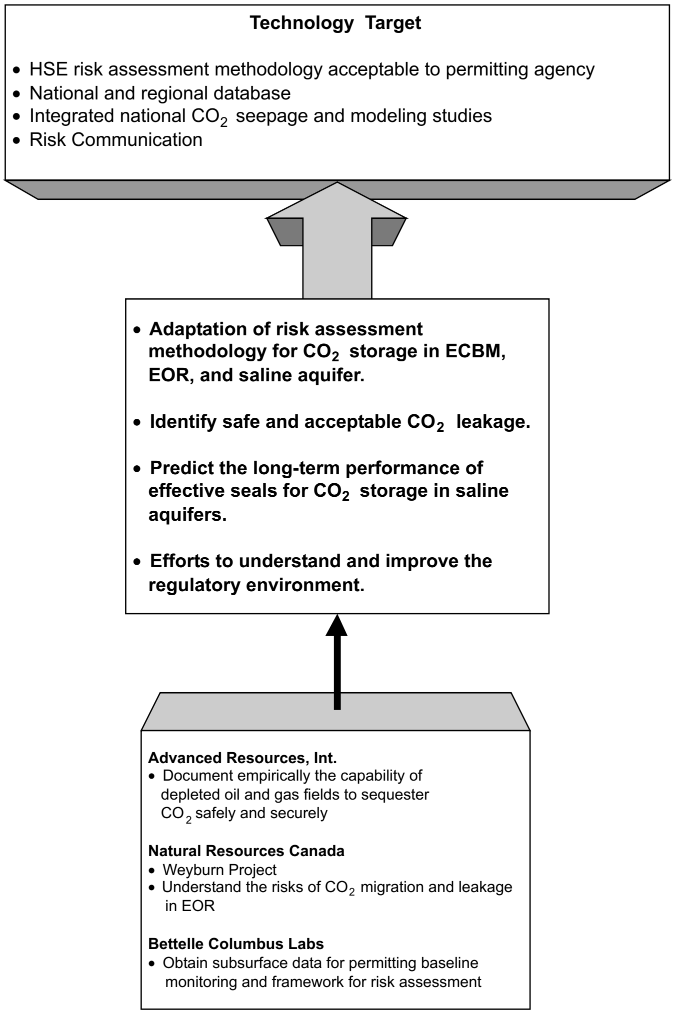


Fig. 3. Health, safety and envirnomental risk assessment.

The Weyburn project will focus on direct injection of CO_2 into a partially depleted carbonate reservoir in the Williston Basin as part of a large scale, commercial EOR operation in Saskatchewan. The miscible CO_2 EOR flood will be monitored from its inception to its conclusion. The study will confirm the ability of an oil reservoir to geologically contain, isolate and permanently store a significant amount of CO_2. It will produce a credible assessment of the permanent containment of injected CO_2, evaluated by long term predictive simulations and formal risk analysis techniques. Such an assessment will help answer questions by regulatory bodies as to the security of large volume CO_2 sequestration/storage, not only in the Williston Basin but also in other areas where geological similarities exist.

Battelle is leading a research team, which includes national laboratories, academia and the energy industry, to conduct site assessment to develop the baseline information necessary to make decisions about a potential CO_2 geologic sequestration demonstration and verification experiment in a saline aquifer. This project will be focused in the Ohio River Valley area, which is home to the largest concentration of coal based electricity generation in the nation. Tests will be conducted to comprehensively characterize the reservoirs, cap rocks and overlying layers. These and other fundamental issues will be used to develop and apply a comprehensive Risk Analysis and Stakeholder Involvement Process for the transport, injection and long term sequestration of CO_2 at a field demonstration site.

5. Knowledge base and technology for CO_2 storage reservoirs

The object for this group of projects is to increase the knowledge base and technology options for sequestering CO_2 in geologic formations. Fig. 4 presents a summary of projects being sponsored by the DOE program in the area.

6. Sequestration in deep coal seams

An attractive option for disposal of CO_2 is sequestration in deep, unmineable coal seams [5]. Not only do these formations have high potential for adsorbing CO_2 on coal surfaces, but the injected CO_2 can displace adsorbed methane, thus producing a valuable by-product and decreasing the overall cost of CO_2 sequestration. Because it has a large internal surface area, coal can store several times more CO_2 than the equivalent volume of a conventional gas reservoir.

To date, only a few experimental enhanced coal bed methane (ECBM) tests involving CO_2 injection have been conducted throughout the world. The sites for these tests show great potential for both CO_2 sequestration and ECBM production. Coal bed thickness is of great importance for ECBM production, both because thicker coal beds have greater volumes and, thus, yield more gas and because advanced production techniques are more applicable in thick coal beds. However, knowledge of this critical parameter is not available for the majority of deep unmineable coal seams.

CONSOL Energy Inc. has initiated a project on CO_2 ECBM production from unmineable coal seams. The world's CBM reserves are estimated at over 30,000 trillion ft^3, but much of this reserve is in coal seams deeper than 1000 m [6]. Efforts to produce CBM from these reservoirs have had

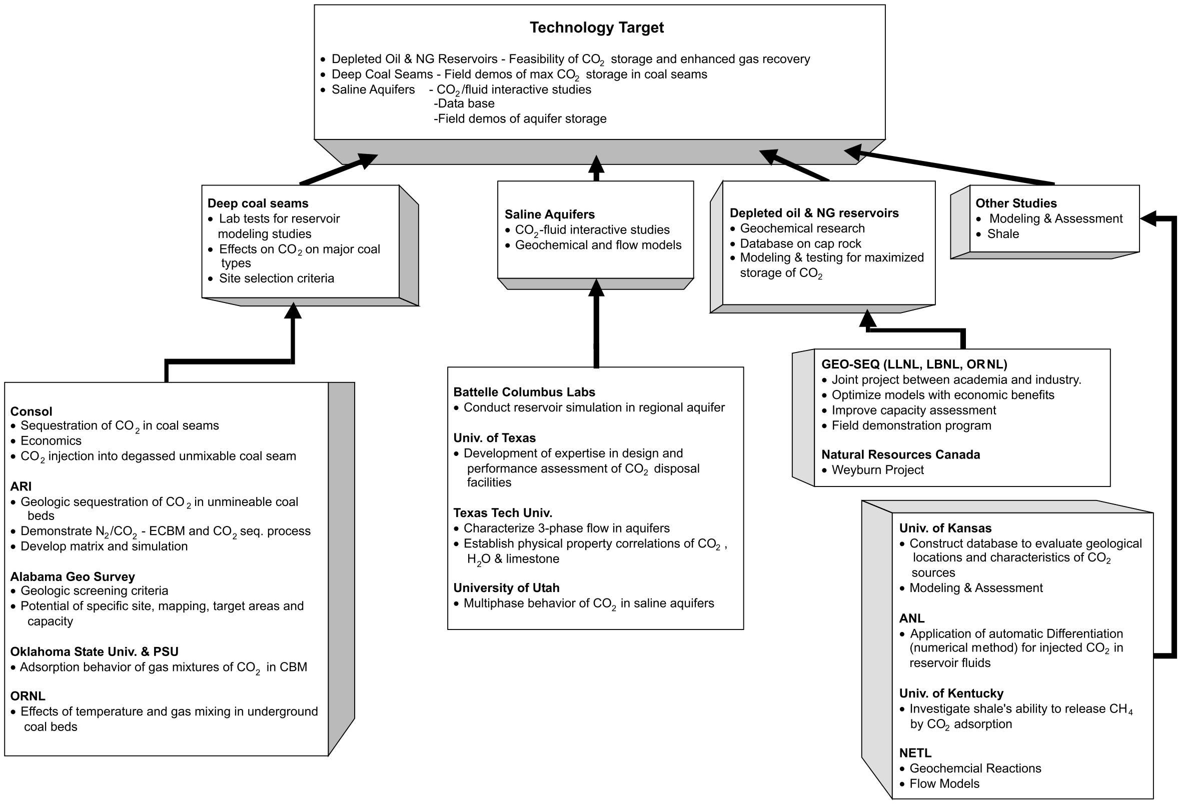


Fig. 4. Knowledge base and technology for CO_2 storage reservoirs.

only limited success because of very low reservoir permeability. A new approach, combining slant (horizontal) holes, hydrofracing with coiled tubing and carbon dioxide flooding is proposed to produce gas from deep, low permeability reservoirs. The project's objectives are to demonstrate the applicability of CBM production using this novel approach and to demonstrate that the injected CO_2 remains sequestered at the intended location.

Advanced Resources International (ARI) is conducting an important project related to storing CO_2 in coal beds. The ARI project involves field testing of injection of CO_2, N_2 and CO_2/N_2 blends into coal seams. The reason for considering N_2 in addition to CO_2 is that N_2 is also an effective methane displacer, and N_2 makes up 80–90% of most flue gas. If flue gas could be sequestered without the need for CO_2 separation and capture, costs could be reduced. The work plan involves analyzing data from field tests at three locations to understand reservoir mechanisms. Technical issues that need to be addressed in this study are flue gas conditioning, compression, delivery and N_2/CH_4 separation. Flue gas injection appears to enhance methane production to a greater degree than is possible with CO_2 alone, while still sequestering CO_2. The information obtained will be used to develop a universal screening model to assess the potential for coal bed CO_2 sequestration in the US. Once developed, the model will be disseminated for use by others.

The Geological Survey of Alabama is conducting a project whose primary goals are to develop a screening model that is widely applicable, to quantify the CO_2 sequestration potential of the Black Warrior CBM region and to use the screening model to identify favorable CO_2 sequestration demonstration sites. The CBM region of the Black Warrior basin is a logical location to develop screening criteria and procedures. According to the US Environmental Protection Agency, Alabama ranks ninth nationally in CO_2 emissions from power plants, and two coal fired power plants are within the CBM region. Production from the Black Warrior basin is now leveling off, and CO_2 injection has the potential to offset the impending decline and extend the life and geographic extent of the region far beyond current projections.

Oklahoma State University is leading an effort to investigate and test the ability of injected CO_2 to enhance CBM production. The specific focus of this project is to investigate the competitive adsorption behavior of methane, CO_2 and nitrogen on a variety of coals. Measurements are focused on adsorption of the pure gases and various mixtures. Data will be taken on coals of varying physical properties at appropriate temperatures, pressures and gas compositions to identify the coals and conditions for which CO_2 sequestration applications are the most attractive.

Mathematical models are being developed to accurately describe the observed adsorption behavior. The combined experimental and modeling results will be generalized to provide a sound basis for performing reservoir simulation studies. These studies will evaluate the potential for injecting CO_2 or flue gas into coal beds to simultaneously sequester CO_2 and enhance CBM production. Future computer simulations will assess the technical and economic feasibility of coal bed CO_2 sequestration at specific candidate injection sites.

Oak Ridge National Laboratory (ORNL) is conducting a program aimed at acquiring critically important technical information for assessing the feasibility of sequestering CO_2 in deep unmineable coal beds. Since this carbon management technology is still in the development phase, fundamental and applied research programs are needed to fill major knowledge gaps. To enable reliable numerical modeling of CO_2 enhanced natural gas production, the effect of CO_2/methane mixing on gas pressure and sorption reactions in deep coal beds must be known quantitatively. Existing computer models are not adequate for this purpose, and experiments must be performed to obtain the data needed to upgrade these models. A significant part of this project involves autoclave measurement of the behavior of CO_2/methane mixtures. The data will be used to predict the behavior of CO_2 when injected into coal beds containing methane.

7. Sequestration in saline aquifers

Another option for geologic sequestration of CO_2 is in saline aquifers. The idea that large aquifers with good top seals can provide effective sequestration sites is a relatively new concept. About two thirds of the US is underlain by deep saline aquifers that have significant sequestration potential [7]. Since the water from such aquifers is typically not suitable for irrigation and other uses, injection of CO_2 does not present a problem for potential future use. Because of the potential for CO_2 to dissolve in the aqueous phase, the storage capacity of saline aquifers is enhanced. However, there are a large number of uncertainties associated with the heterogeneous reactions that may occur between CO_2, brine and minerals in the surrounding strata, especially with respect to reaction kinetics.

There is a growing base of experience with CO_2 disposal in aquifers. One large project being carried out by Statoil involves recovering the CO_2 in natural gas from the Sleipner Vest offshore gas field in Norway at a rate of one million tonnes per year and reinjecting it into a nearby aquifer under the North Sea [8]. CO_2 migration is currently being monitored. Data from this project is contributing to the growing scientific confidence in the reliability of storing CO_2 in saline aquifers. However, more research, field testing, modeling and monitoring are needed to reduce the uncertainties relating to CO_2 storage in these formations.

Battelle Memorial Institute is managing an important project, the objective of which is to design an experimental CO_2 injection well and get it ready for permitting. Tasks involved include subsurface geologic assessment in the vicinity of the experimental site, seismic characterization of the site, borehole drilling to characterize the reservoir and cap rock formations, injection and monitoring system design and risk assessment. The proposed well site is to be located in the panhandle of West Virginia. This site has the advantage of providing access to both saline formations and deep coal beds. It is also in close proximity to a number of power plants that could serve as potential CO_2 sources. Another geologic factor in the vicinity of the site is the formation depth, at about 9000 ft, which provides significant cap rock containment potential and separation from freshwater. To obtain a more realistic assessment of CO_2 breakthrough, a 2-D seismic survey will be performed; a 3-D or 4-D survey will also be performed in preparation for future injection.

The Bureau of Economic Geology at the University of Texas is leading a research team to conduct a CO_2 sequestration field demonstration in a brine bearing formation near Houston, Texas. Two experiments will be conducted, the first involving a small volume of CO_2 using a single well for both injection and monitoring and the second using one well for injection and a second up-structure well for monitoring CO_2 migration. Response will be monitored both within the injection sandstone bed and in an overlying thin sandstone bed.

The study site provides for a rapid startup by using existing idle wells and has a low risk of adverse impacts because injection will take place in a hydrologically isolated reservoir compartment of a well known geologic structure. This project will extend the demonstration of modeling and monitoring capabilities for sequestration into a geologic formation for which very large scale sequestration is feasible in an area where significant CO_2 is produced. Texas is the state with the largest volume of CO_2 emissions [9].

Texas Technical University is conducting a project to develop a well logging technique using nuclear magnetic resonance (NMR) to characterize geologic formations, including the integrity and quality of the cap rock. Since well logging using NMR does not require coring, it can be performed more quickly and efficiently. Prior studies have identified several issues as impediments to the economic viability of sequestering CO_2 in deep saline aquifers and other geologic formations. These issues include the injection rate, the pressure required to achieve an economic throughput and how to assure the long term containment of CO_2. This research is aimed at determining suitable sites for injection of CO_2, sites at which artificial zones of high permeability can be created by controlled hydraulic fracturing. Hydraulic fracturing could reduce the number of injection wells required by an order of magnitude.

The University of Utah is heading a project that is studying naturally occurring CO_2 saline aquifers in the Colorado Plateau and Southern Rocky Mountains. These formations serve as natural analogs for CO_2 sequestration in saline aquifers. Studying them can provide much useful data to verify computer models. Also, small amount of natural leakage from these reservoirs is occurring, and studying these leaks can provide insight into the environmental problems caused by leaks, under what circumstances leaks can occur and how they can be mitigated. The project also includes numerical simulation of CO_2 sequestration in these formations, including reactive modeling, that is modeling that accounts for chemical reactions between the formation rocks and CO_2.

8. Sequestration in depleted oil and gas reservoirs

Yet another option for geologic sequestration of CO_2 is in depleted oil and gas reservoirs. Since such formations are generally gas tight, the risk of leakage is expected to be minimal. Furthermore, there is the potential for enhanced oil and gas production, the sale of which can help mitigate sequestration costs. Most EOR projects in the US are in the Permian Basin of Texas. Most of the CO_2 for these projects is being transported by pipeline from natural CO_2 reservoirs in Colorado, New Mexico and Wyoming. It is anticipated that, with high oil prices, recovery of CO_2 using the flue gas of coal burning power plants could be profitable for EOR use in the region.

The GEO-SEQ Project is being conducted by a consortium of national laboratories, educational institutions, and private industry firms. The project's goal is to reduce the cost of sequestration, develop a broad suite of sequestration options and ensure that long term sequestration practices are effective and do not introduce any new environmental problems. This objective is being approached by dividing the effort into four targeted interrelated tasks: cost optimization, monitoring technology, performance assessment models and capacity assessment. One important task is to develop methods for simultaneously optimizing sequestration of CO_2 in depleted oil and gas fields and increased oil and gas production. Such methods would have obvious multiple benefits. Results will lay the groundwork for rapidly evaluating performance at candidate sequestration sites, as well as monitoring the performance of CO_2 enhanced oil and gas recovery.

Natural Resources Canada is conducting a study of the injection of CO_2 into the Weyburn Unit. Understanding the mechanism, reservoir storage capability and the economics of CO_2 sequestration requires mapping the migration and distribution of the existing formation fluids, as well as the injected fluids. The project is focused on the acquisition of information from the enhanced oil recovery operation, on conducting geological, geophysical and geochemical assessments and on reservoir model simulations.

9. Other studies

DOE is also supporting other related studies. These mainly involve computer model development and project assessment.

The Midcontinent Interactive Digital Carbon Atlas and Relational Data Base (MIDCARB) is a joint project among the Geological Surveys of Illinois, Indiana, Kansas, Kentucky and Ohio being coordinated by the University of Kansas. The purpose of MIDCARB is to enable the evaluation of the potential for carbon sequestration in the participating states. When completed, the digital spatial data base will allow users to estimate the amount of CO_2 emitted by major sources in relation to geologic reservoirs that can provide safe and secure sequestration over geologic time periods. MIDCARB is organizing and enhancing critical information about CO_2

sources and developing the technology needed to access, query, model, analyze, display and distribute natural resource data related to carbon management.

Argonne National Laboratory is working on the development of improved computer models of the sequestration process. There is growing interest in linking reservoir flow models to geochemical models. If the formation has an aqueous phase, the injected CO_2 will dissolve in the reservoir liquid. In this case, the reactions of the CO_2-rich fluid with the host rock to form minerals should also be considered. More importantly, a geological CO_2 storage reservoir simulation must be effective in developing a design for optimal injection. The key element in finding the optimal CO_2 injection scheme is to work with an inverse modeling and sensitivity analysis tool for forward mode reservoir simulations.

Argonne National Laboratory is applying automatic differentiation (AD) as an alternative to the usual finite difference method of calculating derivatives. This technique will interface with existing geological CO_2 sequestration models to improve both the accuracy and speed of derivative computations. By using the new models generated by the AD method, it is possible to automatically determine the sensitivities of reservoir simulation output variables to any given independent input parameter, thus making the computer design of an optimal CO_2 storage scheme feasible.

The University of Kentucky Research Foundation is conducting an analysis of Devonian black shale in Kentucky for its potential for CO_2 sequestration and methane production. In testing the hypothesis that organic rich shales can adsorb significant amounts of CO_2 while releasing methane, the objective will be to characterize the shale, determine its CO_2 adsorption isotherm, the relationship of shale properties to CO_2 adsorption capacity, the effect of CO_2 adsorption on methane release and whether there are zones in the shale that have higher CO_2 adsorption capability and the extent of such zones.

The National Energy Technology Center (NETL) is pursuing a number of projects aimed at increasing the knowledge base relative to geologic sequestration of CO_2. One project, being conducted jointly with the US Geological Survey, has the objective of conducting an experimental study to assess the role of the chemistry of formation water on CO_2 solubility and the role of rock mineralogy in determining the potential for CO_2 sequestration through geochemical reactions. Another project being pursued in conjunction with a number of other organizations is aimed at providing guidelines for drilling new CBM production wells and determining what factors contribute to poor methane production/CO_2 sequestration performance. A third project, being conducted with West Virginia and Clarkson Universities, is aimed at building a system of flow equations relevant for core and field studies that incorporates unstable pore level flow patterns and to compare results with those of experiments and existing flow theory. A fourth project, involving Clarkson and Pennsylvania State Universities and CONSOL Energy Inc., has the objective to optimize the quantity of CO_2 that can be sequestered, the economic viability of coal bed sequestration, and the environmental acceptability of the technology.

10. BP carbon capture project, an example of integrated collaboration

An important cross-cutting driver for CO_2 sequestration R&D is integrated collaboration. An excellent example of this is the BP Carbon Capture Project (CCP). DOE is a partner in the CCP, an international technology development effort, involving the US, Norway and the European Union and directed toward the development of CO_2 capture and sequestration technology [10]. The objective is to share in program development in order to leverage funding and results and reduce duplication. BP, Chevron-Texaco, ENI (Italy), Shell, Norsk Hydro (Norway), Pan Canadian (Canada), Statoil (Norway) and Suncor (Canada) have formed the CCP, recognizing the advantages in pooling resources, experience and innovation to make the delivery of the needed technology more efficient and to provide the best opportunity for success.

The approach of the CCP is to define relevant scenarios and technology targets, solicit proposals and make awards. Technology teams, using various economic models, provide continuous project evaluation so that resources can be concentrated on the most promising technologies. Fig. 5 presents an overview of projects being conducted by the CCP. This figure shows that the CCP incorporates a wide spectrum of activities, involving all the areas already discussed. In general, these projects have smaller budgets and a shorter time frame than the projects discussed previously. The idea is to generate information that can feed into other development work as rapidly as possible.

Some projects are examining problems associated with long term monitoring and verification of formation integrity. A project is underway to develop a new method of monitoring gas injection

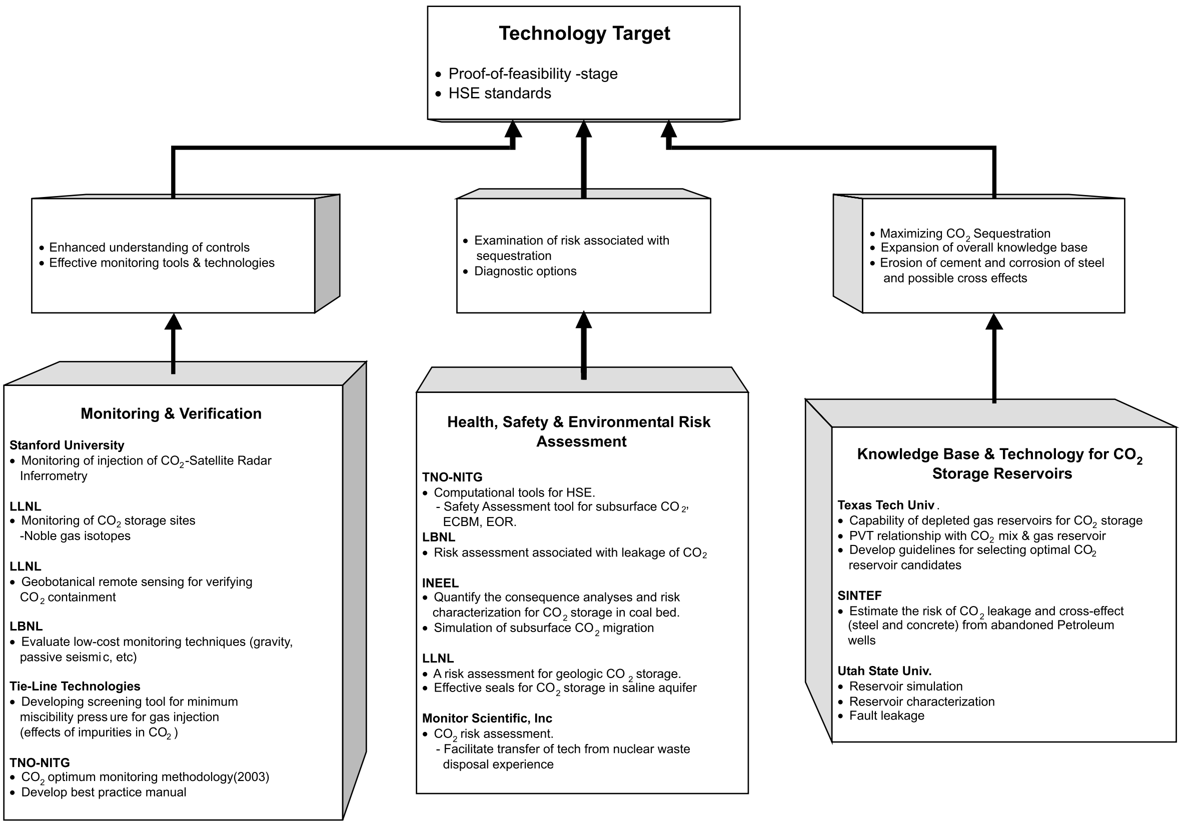


Fig. 5. BP carbon capture project (CCP).

using space borne satellite radar technology. This approach will permit observation of changes in surface elevation as small as 1 cm at 20 m spacing over an area 100 km square, so that the spatial distribution of elevation changes may be mapped in detail.

Another project is developing methodology and computational tools for health, safety and environmental risk assessment of geological CO_2 sequestration in various geologic strata of the North Sea region. This work will be integrated with the parallel system analysis activities of the Weyburn project.

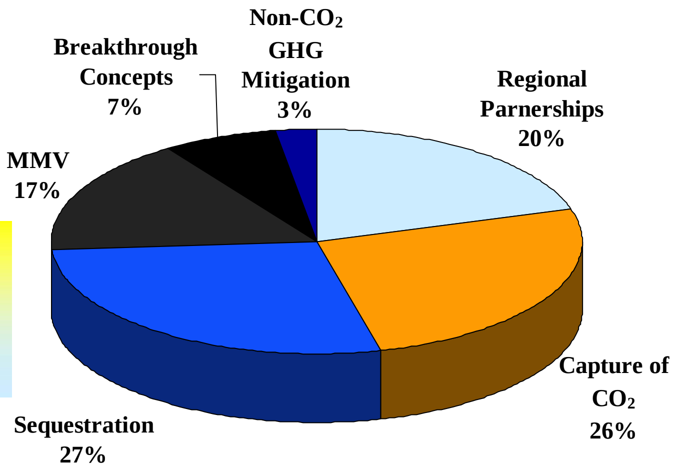
11. Conclusions

The DOE Carbon Sequestration Program is developing a portfolio of technologies that hold great potential for the permanent sequestration of CO_2 in geologic formations. The programmatic timeline is to demonstrate a series of safe and cost effective greenhouse gas mitigation technologies at the commercial scale by 2012, with deployment leading to substantial market penetration beyond 2012. Developments are directed toward substantial improvement in performance and costs compared to the current state-of-the-art. Wide deployment of these technologies holds great promise to slow the growth of GHG emissions to the atmosphere in the near term while ultimately leading to stabilized emissions towards the middle of the 21st century. This paper has presented a brief overview of the portion of the DOE Carbon Sequestration Program dedicated to geologic storage of CO_2. More details on these and other R&D projects in the portfolio can be found at the referenced web site [2].

References

[1] Schmidt CE, Klara S, Srivastava RD. DOE Carbon Sequestration Program—US Department of Energy. Proceeding of the Electric Utilities Environmental Conference 2002, Tucson, Arizona.
[2] Available from: www.netl.doe.gov/coalpower/sequestration (August 2002).
[3] Klara S, Srivastava RD. Integrated collaborative technology development for CO_2 separation and capture—US Department of Energy RD&D. Environmental Progress 2002;21:247.
[4] Stevens SH, Pearce JM, Riggs AAJ. National analogs for geological storage of CO_2. First National Conference on Carbon Sequestration, Washington, DC, May 15–17, 2001.
[5] Byrer CW, Guthrie HD, Coal deposits: potential geological sink for sequestering carbon dioxide emissions from power plants. In: Eliasson C, Riemer P. Wokaun A, editors. Greenhouse Gas Control Technologies: Proceedings of the Fourth International Conference on GHG Control Technologies. Amsterdam: Pergamon. 1998, p. 181–87.
[6] Thakur PC, Statnick RM, Cairns G. Coalbed methane production from deep coal seams. In: Chiu C, Srivastava RD, Mallinson R, editors. Proceedings of the Second Topical Conference on Natural Gas Utilization, AIChE Spring National Meeting, March 2002.
[7] Bergman PD, Winter EM. Disposal of carbon dioxide in aquifers in the US. Energy Convers Mgmt 1995;36:523.
[8] Kaarstad O. Emission-free fossil energy from norway. Energy Convers Mgmt 1992;33:781.
[9] Hovorka SD. Optimal geological environments for CO_2 disposal in aquifers in the United States. University of Texas at Austin, Bureau of Economic Geology, Technical Report, DE-AC26-98FT40417; 2001.
[10] Hill G. Available from: www.CO2captureproject.org (December 2001).

Carbon Sequestration
FY 2005 Budget Total = $46 Million



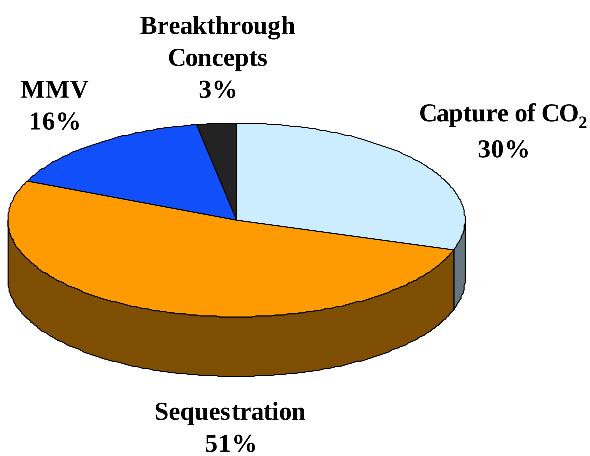
68 Contracted Projects

14 In-House Projects

NETL

January 2005

Carbon Sequestration
Focus Area
FY 2005 Budget = $6.9 Million

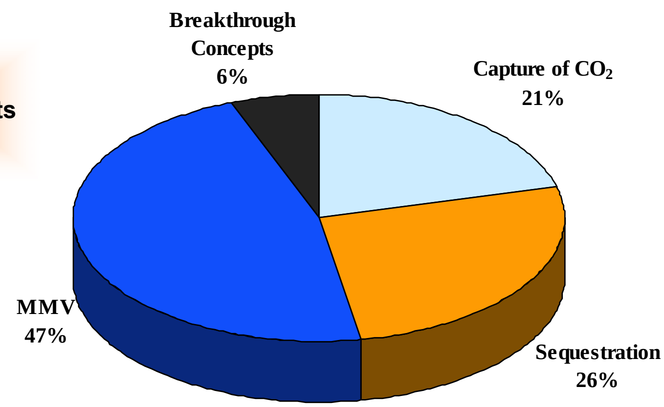


NETL

January 2005

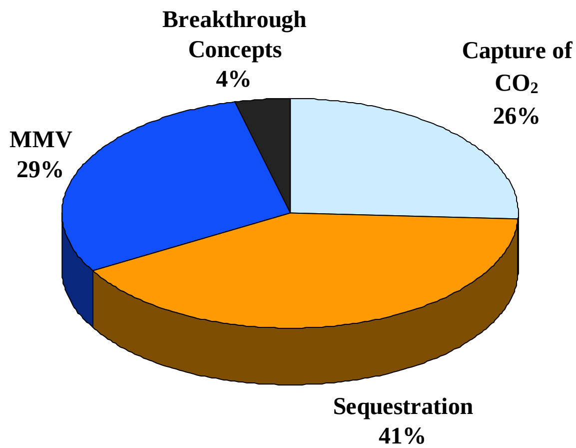
Carbon Sequestration
National Laboratories
FY 2005 Budget = $5.3 Million

15 Projects



January 2005

Carbon Sequestration
Focus Area & National Laboratories
FY 2005 Budget = $12.2 Million



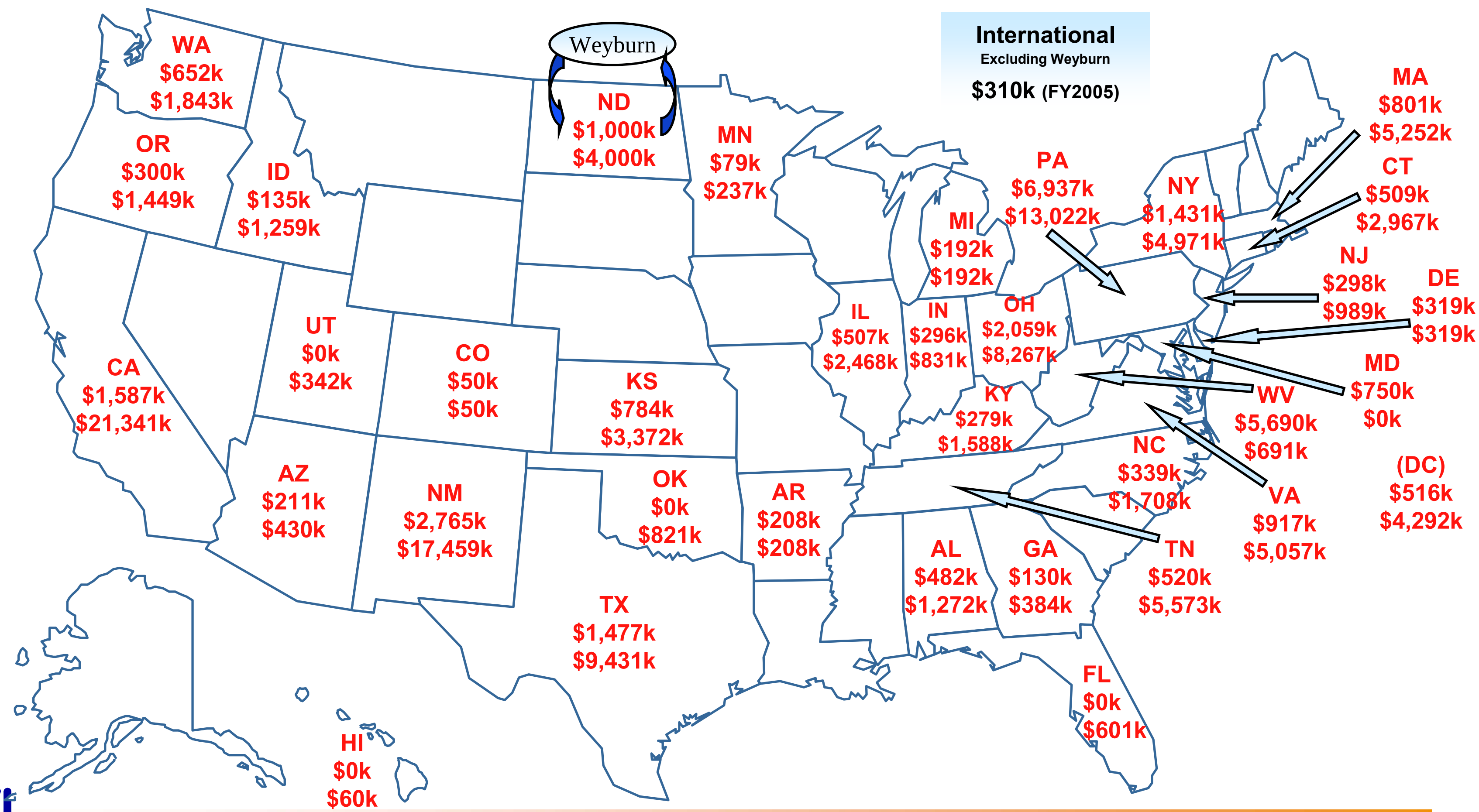
January 2005

Carbon Sequestration State Budget Analysis

Regional Partnerships

MRCSP	MGSC	SRCSP	SRPCS	WCRCSP	NRGPR	PCRP
$861k	$453k	$531k	$520k	$260k	$407k	$1,016k
$2,250k	$1,782k	$1,970k	$1,370k	$1,130k	$1,252k	$2,267k

LEGEND
FY05 Cost
(projects & support)
Total Government
(life of projects only)



General/Mixed Fact Sheets

Technology Fact Sheets

- Coal Technologies Offer CO_2 Capture Benefits
- Coal-Based IGCC Offers CO_2 Capture Benefits for Oil Recovery

Program Fact Sheets

- Sequestration of Carbon Dioxide Emissions in Geologic Formations
- Carbon Sequestration Through Enhanced Oil Recovery
- Terrestrial Sequestration Program
- Sequestration of Carbon Dioxide Emissions in the Ocean
- Field Tests Demonstrate Secure CO_2 Storage in Underground Formations
- The Cost Of Carbon Dioxide Capture and Storage in Geologic Formations
- Lake Nyos and Mammoth Mountain: What Do They Tell Us About the Security of Engineered Storage of CO_2 Underground?
- Risk Assessment for Long-Term Storage of CO_2 in Geologic Formations

R&D Fact Sheets

- Carbon Sequestration Science
- Sorbent and Catalyst Preparation Facilities
- Advanced Analytical Instrumentation and Facilities for In Situ Reaction Studies
- Small-Scale Facilities for Air Pollution Research

TECHNICAL **facts**

U.S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

10/2002

CONTACT POINTS

Scott M. Klara
Sequestration Product Manager
U.S. Department of Energy
National Energy Technology Laboratory
626 Cochran Mill Road
P.O. Box 10940
Pittsburgh, PA 15236-0940
412-386-4864
scott.klara@netl.doe.gov

Mildred B. Perry
U.S. Department of Energy
National Energy Technology Laboratory
626 Cochran Mill Road
P.O. Box 10940
Pittsburgh, PA 15236-0940
412-386-6015
mildred.perry@netl.doe.gov

CUSTOMER SERVICE

800-553-7681

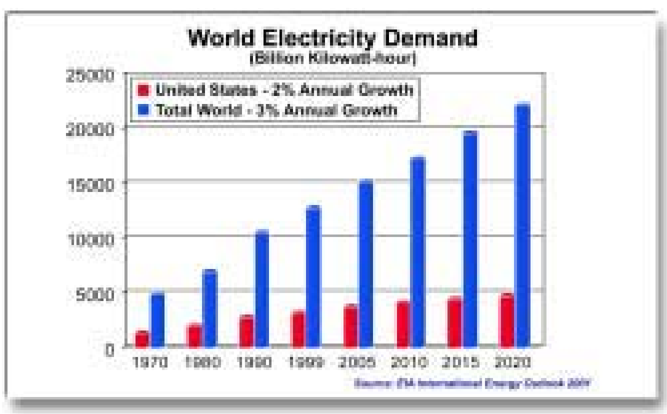
WEBSITE

www.netl.doe.gov

"DOE-EPRI Report 1000316, 12/2000" is available on the web at www.netl.doe.gov/products/power1/gasification/publications/EpriReport.PDF

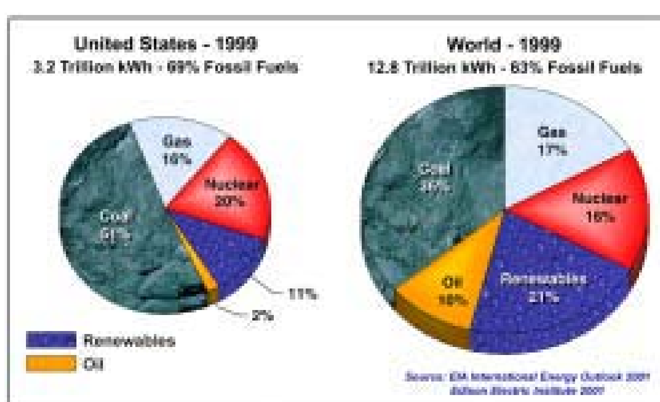
COAL TECHNOLOGIES OFFER CO_2 CAPTURE BENEFITS

With potential implications surrounding global climate change and carbon dioxide (CO_2), technology and policy options are being investigated for mitigating carbon dioxide emissions. Electric power generation represents one of the largest CO_2 contributors in the United States. Electricity consumption is expected to grow and fossil fuels will continue to be the dominant fuel source. Therefore, fossil fuel based power generation can be expected to provide an even greater CO_2 contribution into the future. Coal fuels more than half of this electric power generation capacity and typically produces the cheapest electricity among all fuel sources. Compared to other fossil fuels, coal suffers inherent CO_2 disadvantages relative to its combustion characteristics and the fact that most coal power plants are old and inefficient. These CO_2 disadvantages present a major challenge to coal-based power generation. Fortunately for coal, off-the-shelf CO_2 capture technologies provide performance and cost benefits for minimizing carbon dioxide emissions relative to other fossil fuel sources.



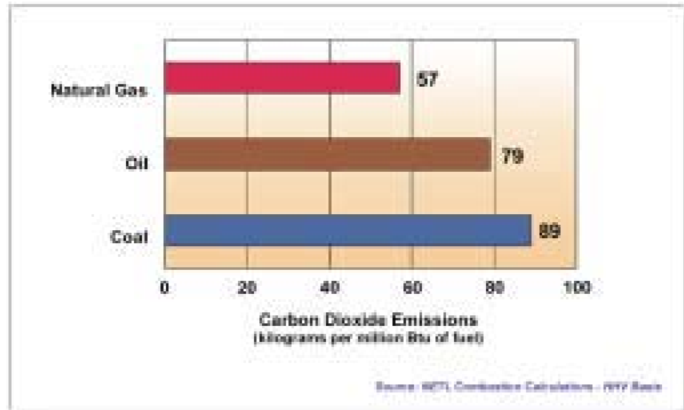
Electricity Use is Growing

Fossil Fuels: Dominant Energy Source for Electricity

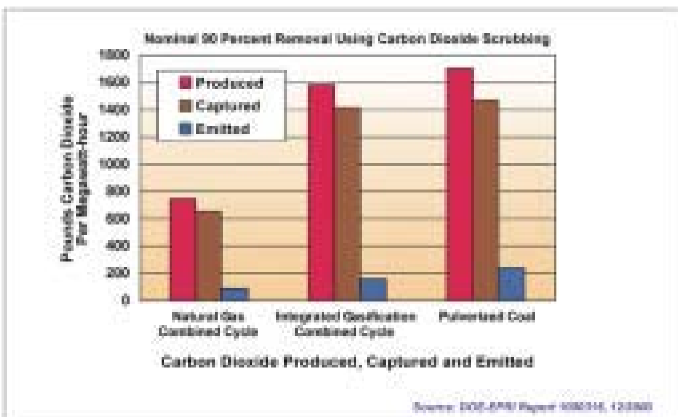


Coal Technologies Offer CO_2 Capture Benefits

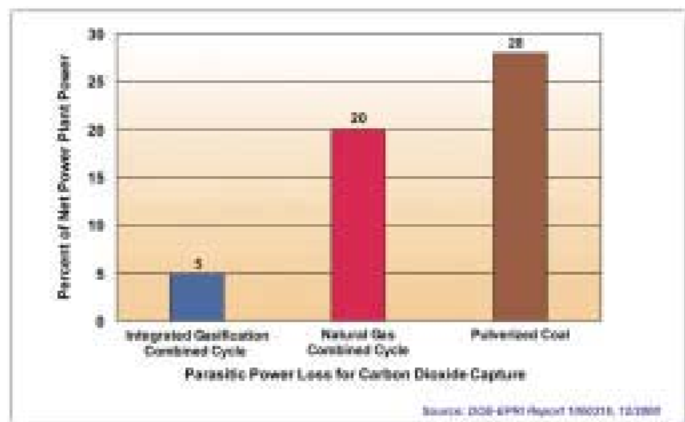
Coal & Electricity Are Major CO_2 Contributors



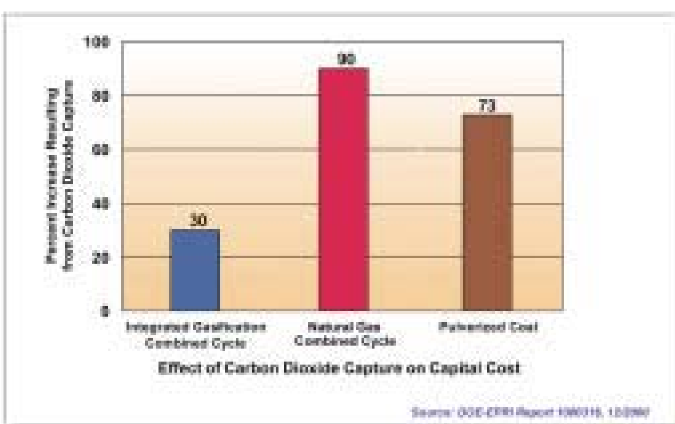
Fossil Fuel CO_2 Emissions



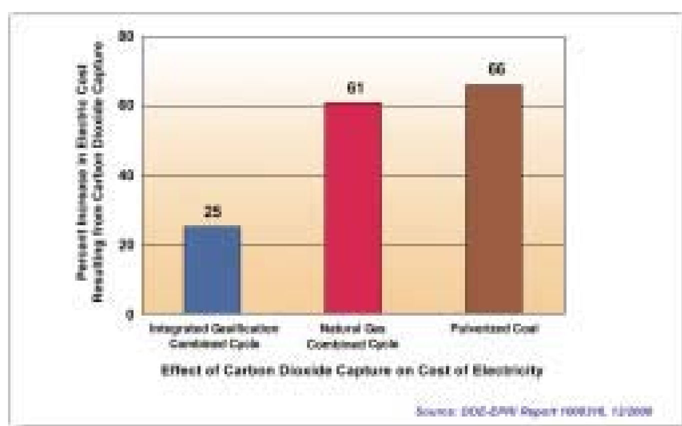
Substantial CO_2 Capture From Coal Power Plants



IGCC Minimizes Energy Penalty of CO_2 Capture



Coal Technologies Minimize Impact on Capital Cost



IGCC Minimizes Impact on Cost of Electricity

TECHNICAL
facts

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

Sequestration

07/2004

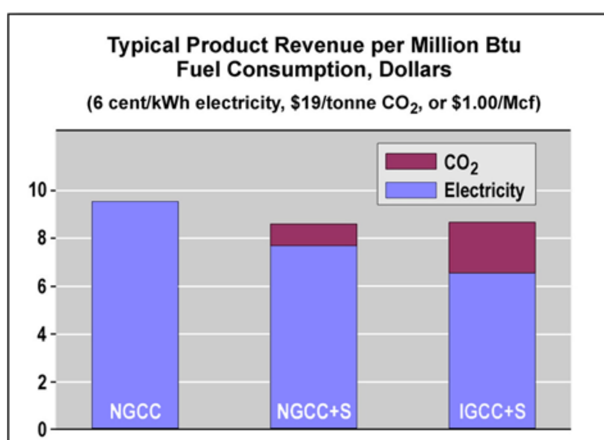
COAL-BASED IGCC OFFERS CO_2 CAPTURE BENEFITS FOR OIL RECOVERY

Background

As the demand for electricity steadily increases and concerns grow about greenhouse gas emissions, scientists are focusing on a coal-based technology that holds promise for addressing these issues. The technology, Integrated Gasification Combined Cycle equipped with a carbon capture and sequestration system (IGCC+S), can produce electricity at a competitive price, clean the environment of the most important greenhouse gas — carbon dioxide (CO_2) — and use the CO_2 as a valuable by-product to recover additional oil from mature reservoirs.

Scientists compared IGCC+S with two other approaches to determine how each would fare in a U.S. market that assumes an increased use of CO_2 to squeeze more oil out of mature reservoirs in a process called Enhanced Oil Recovery (EOR). The two other approaches were Natural Gas Combined Cycle (NGCC) and NGCC equipped with CO_2-capture technologies (NGCC+S). IGCC+S and NGCC+S, now in various phases of research and development, should be ready for commercialization within the decade. Selling the captured CO_2 for use in EOR projects could help offset the costs of these technologies while producing afford-able electricity and cleaning the environment.

At current and expected prices for natural gas, NGCC is the least expensive generating technology available. Economic projections show that it will provide the majority of additional generating capacity required by the United States over the next several decades. The present study was undertaken to determine if IGCC+S could be cost-competitive with NGCC if the captured CO_2 were marketable for use in EOR. This IGCC+S technology captures 90 percent of generated CO_2, which means that the net emission of CO_2 would only be about one-fifth as large per kilowatt-hour as emissions from NGCC.



CONTACT POINTS

John A. Ruether
Senior Engineer and Technical Advisor
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4832
ruether@netl.doe.gov

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

Coal-Based IGCC Offers CO_2 Capture Benefits for Oil Recovery

Description

Scientists from the U.S. Department of Energy's (DOE) National Energy Technology Laboratory and the Pacific Northwest National Laboratory compared the economics of the three fossil-fuel technologies. They conducted the study to determine the price of electricity and the rate of return on invested capital expected for each of the three fossil-fuel systems. They further assumed that the systems would be built by 2010 and would operate for 20 years. Assumptions on fuel price, thermal efficiency, costs of coal and natural gas, and selling price of electricity and CO_2 were taken into account. The comparison resulted in the following conclusions.

NGCC's CO_2 emissions are less than half of those produced by an IGCC without carbon capture. But, an IGCC+S produces only one-fifth the carbon emissions of the most efficient NGCC. If reducing CO_2 emissions becomes important, an IGCC+S represents a significant improvement over NGCC.

NGCCs equipped to achieve 90 percent carbon capture are not as efficient as an IGCC+S, and the capital cost for providing capture is greater for NGCC than for IGCC. The cost difference is attributed to differences in the capture methods employed in the two generation approaches: from the flue gas in a NGCC and from a synthesis gas in an IGCC. The study indicates that the price of electricity generated by NGCC+S would be higher than that generated by either NGCC (without capture) or IGCC+S.

A large factor in the comparative costs of coal- and gas-based generation systems is fuel price. Compared with the price of oil and natural gas, the price of coal is expected to be stable. In fact, coal prices are expected to decline in the next two decades while the price of natural gas is projected to more than double for the same period. Price projections prepared by DOE's Energy Information Administration were used in the study. A large variability in the price of oil is also projected. In the study, the value of CO_2 for practice of EOR was estimated from published predictions of oil prices by using an historic linkage of prices for the two commodities.

Benefits

When they completed their study, the scientists concluded that IGCC+S could produce electricity profitably in a competitive market with no government subsidy for avoided carbon emissions, as is sometimes invoked as a means of bringing low carbon-emitting technology into the market. The profitability of NGCC is expected to be greater than that of IGCC+S, but uncertainty associated with the return on investment is greater for NGCC than for IGCC+S because of uncertainty of natural gas prices in the future. And finally, the potential for oil recovery is significant. When CO_2 is used for EOR, it can yield an additional 7 to 15 percent of the original oil in a reservoir and extend the life of the field by 15 to 30 years.

CO_2-EOR: The U.S. Landscape

- 66 Projects: > 190,000 bbl/day enhanced production
- 5 CO_2 Domes: > 1300 MMcfd, 30 TCF recoverable reserves (50+ years worth)
- Other CO_2 Sources
- CO_2 Pipeline Infrastructure

PROGRAM
facts
U.S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

10/2002

CONTACT POINTS

Scott M. Klara
Sequestration Product Manager
412-386-4864
scott.klara@netl.doe.gov

Charles Byrer
Project Manager
Environmental Projects Division
304-285-4547
charles.byrer@netl.doe.gov

Perry Bergman
Project Manager
Environmental Projects Division
412-386-4890
perry.bergman@netl.doe.gov

ADDRESS

National Energy Technology Laboratory

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

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

CUSTOMER SERVICE

800-553-7681

WEBSITE

www.netl.doe.gov

SEQUESTRATION OF CARBON DIOXIDE EMISSIONS IN GEOLOGIC FORMATIONS

Sequestration of Carbon Dioxide Emissions in Geologic Formations

This project is based on the fact that geologic formations, such as oil fields, coalbeds, and saline aquifers, are likely to provide the first large-scale opportunity to sequester concentrated CO_2 emissions. Researchers are trying to determine what effective, safe, and cost-competitive options are available for geologic storage of CO_2 emissions generated from coal, oil, and gas power plants. The research targets formations within 500 km of each power plant in the U.S. The U.S. goal is to reduce the cost of carbon sequestration to $10 or less per net ton of carbon by 2015.

Geologic Sequestration of CO_2 in Deep, Unminable Coalbeds: An Integrated Research and Commercial-Scale Field Demonstration Project

Advanced Resources International, B-P Amoco and Shell Oil are using existing recovery technology to evaluate the viability of storing CO_2 in deep unminable coal seams in the San Juan Basin in northwest New Mexico and southwestern Colorado. The knowledge gained will be used to verify and validate gas storage mechanisms in coal reservoirs, and to develop a screening model to assess CO_2 sequestration potential.

Maximizing Storage Rate and Capacity, and Insuring the Environmental Integrity of Carbon Dioxide Sequestration in Geological Formations

Texas Tech University and its research partners are using nuclear-magnetic resonance well-logging techniques to identify suitable geologic formations for CO_2 storage. Understanding hydraulic fracturing will enable researchers to predict of the behavior of gas in targeted formations to minimize the number of injection wells, while increasing the injected gas volume.

PROJECTS

Geologic Sequestration of CO_2 in Deep, Unminable Coalbeds: An Integrated Research and Commercial-Scale Field Demonstration Project

Principal Investigator:
Scott Reeves, 713-780-0815

Partners: Advanced Resources International, Houston, Texas; B-P Amoco, Houston, Texas; Shell-CO_2 , Houston, Texas

Maximizing Storage Rate and Capacity and Insuring the Environmental Integrity of Carbon Dioxide Sequestration in Geological Formations

Principal Investigator:
Alan Graham, 806-742-3553

Partners: Texas Tech University, Lubbock, Texas; Terra Tek, Salt Lake City, Utah; Sandia National Laboratory, Albuquerque, New Mexico; University of New Mexico, Albuquerque, New Mexico

Reactive, Multiphase Behavior of CO_2 in Saline Aquifers Beneath the Colorado Plateau

Principal Investigator:
Richard Allis, 801-581-7849

Partners: University of Utah, Energy and Geoscience Institute, Salt Lake City, UT; Industrial Research Limited (IRL), New Zealand

Geologic Screening Criteria for Sequestration of CO_2 in Coal: Quantifying the Potential of the Black Warrior Coalbed Methane Fairway, Alabama

Principal Investigator:
Jack Pashin, 205-349-2892

Partners: Geological Survey of Alabama, Tuscaloosa, AL; Alabama Power Company, Birmingham, Alabama; Jim Walter Resources, Brookwood, Alabama; University of Alabama, Birmingham, Alabama

Reactive, Multiphase Behavior of CO_2 in Saline Aquifers Beneath the Colorado Plateau

The University of Utah is leading an effort to conduct an in-depth study of deep saline reservoirs in the Colorado Plateau and Rocky Mountain region. The study will enable researchers to determine how much CO_2 can be stored, what happens to the stored gas, and the long-term environmental risks associated with the storage.

Geologic Screening Criteria for Sequestration of CO_2 in Coal: Quantifying the Potential of the Black Warrior Coalbed Methane Fairway, Alabama

The Geological Survey of Alabama and its partners are conducting research to determine the amount of CO_2 that can be stored in the Black Warrior coalbed methane region of Alabama. The effort is focused on developing a broad-based geologic screening model, quantifying CO_2 storage potential of the Black Warrior coalbed methane region, and applying the model to identify additional sites.

Experimental Evaluation of Chemical Sequestration of Carbon Dioxide in Deep Aquifer Media

This project involves Battelle Laboratories evaluating and examining factors that affect the geological and geochemical storage of CO_2 in deep saline formations in the Midwestern U.S. Research presently indicates that the most promising long-term option for sequestration is to dispose of CO_2 in a dense, supercritical phase in deep saline sandstone formations.

Optimal Geological Environments for Carbon Dioxide Disposal in Saline Aquifers in the United States

The University of Texas at Austin's Bureau of Economic Geology is developing criteria for characterizing optimal conditions and characteristics of saline aquifers that can be used for long-term storage of CO_2. A regional U.S. data inventory of saline water-bearing formations is also being developed.

Sequestering Carbon Dioxide in Coalbeds

Oklahoma State University is leading an effort to develop, test, and investigate the ability of injected carbon dioxide to enhance coalbed methane production. The research will investigate competitive adsorption behavior of methane, CO_2, and nitrogen on the surface of a variety of coals to determine how much CO_2 is needed to displace the methane.

The GEO-SEQ Project

Lawrence Berkeley, Lawrence Livermore, and Oak Ridge National Laboratories and their partners are investigating safe and cost-effective methods for geologic sequestration of CO_2. Targeted tasks address the following: (1) Siting, selection, and longevity of the optimal sequestration sites; (2) lowering the cost of geologic storage; and (3) Identification and demonstration of cost-effective and innovative monitoring technologies to track migration of CO_2.

Geologic Sequestration of CO_2

Sandia National Laboratory and Los Alamos National Laboratory have partnered with an independent producer, Strata Production Company, to investigate down-hole injection of CO_2 into a depleted oil reservoir. A comprehensive suite of computer simulations, laboratory tests, field measurements, and monitoring efforts will be used to understand, predict, and monitor the geomechanical, geochemical, and hydrogeologic processes involved. The observations will be used to calibrate, modify, and validate the modeling and simulation tools.

Experimental Evaluation of Chemical Sequestration of Carbon Dioxide in Deep Aquifer Media

Principal Investigator:
Neeraj Gupta, 614-424-3820

Participant: Battelle Columbus Laboratories, Columbus, Ohio

Optimal Geological Environments for Carbon Dioxide Disposal in Saline Aquifers in the United States

Principal Investigator:
Susan Hovorka, 512-471-1534

Participant: University of Texas at Austin, Bureau of Economic Geology, Austin, TX

Sequestering Carbon Dioxide in Coalbeds

Principal Investigators:
K. Gasem and R. Robinson, 405-744-9498

Partners: Oklahoma State University, Stillwater, Oklahoma; Pennsylvania State University, Department of Energy and Geo-Environmental Engineering, State College, PA

The GEO-SEQ Project

Principal Investigator:
Sally Benson, 510-486-7071/7714

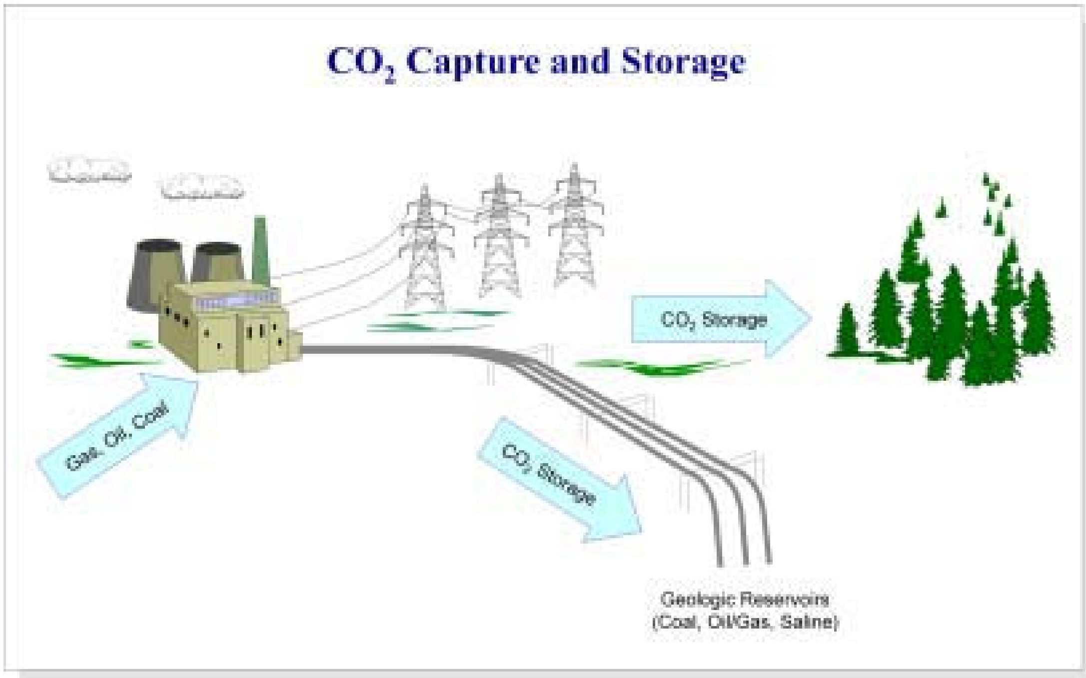
Partners: Lawrence Berkeley National Laboratory, Berkley, California; Lawrence Livermore National Laboratory, Livermore, California; Oak Ridge National Laboratory, Oak Ridge, Tennessee; Stanford University, USGS, Texas Bureau of Economic Geology, Alberta Research Council, Chevron, Texaco, Pan Canadian Resources, Shell CO_2, BP-Amoco, and Statoil, Norway

Geologic Sequestration of CO_2

Principal Investigator:
Henry Westrich, 505-844-9092

Partners: Sandia National Laboratory, Los Alamos National Laboratory, Strata Production Company

SEQUESTRATION OF CARBON DIOXIDE EMISSIONS IN GEOLOGIC FORMATIONS



Range of Estimates for CO_2 Sequestration in U.S. Geologic Formations

Geologic Formation	Capacity Estimate (GtC)	Source
Deep saline reservoirs	1-130	Bergman and Winter 1995
Natural gas reservoirs in the United States	25 [a] 10 [b]	R.C. Burruss 1977
Active gas fields in the United States	0.3 / year [c]	Baes et al. 1980
Enhanced coal-bed methane production in the United States	10	Stevens, Kuuskraa, and Spector 1998

a. Assuming all gas capacity in the United States is used for sequestration
b. Assuming cumulative production of natural gas is replaced by CO_2
c. Assuming that produced natural gas is replaced by CO_2 at the original reservoir pressure

PROGRAM facts

Sequestration

07/2004

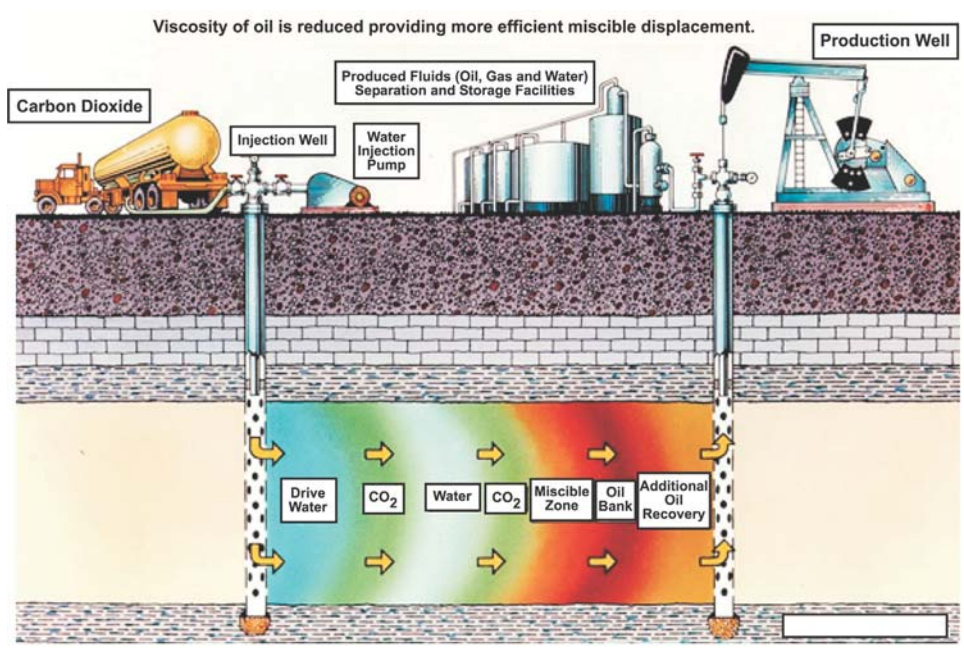
U.S. Department of Energy
Office of Fossil Energy
National Energy Technology Laboratory

Carbon Sequestration through Enhanced Oil Recovery

Description/Background

Enhanced Oil Recovery (EOR) refers to techniques that allow increased recovery of oil in depleted or high viscosity oil fields. In 2000, EOR projects produced a total of 780,000 barrels of oil per day (Moritis, 2000), almost 12 percent of the total U.S. production. One method of EOR, carbon dioxide flooding (CO_2 EOR), has the potential to not only increase the yield of depleted or high viscosity fields, but also to sequester carbon dioxide that would normally be released to the atmosphere. In general terms, carbon dioxide is flooded into an oilfield through a number of injection wells drilled around a producing well. Injected at a pressure equal to or above the minimum miscibility pressure (MMP), the CO_2 and oil mix and form a liquid that easily flows to the production well. Pumping can also be enhanced by flooding CO_2 at a pressure below the MMP, swelling the oil and reducing its viscosity.

CO_2 EOR has been used by the oil and gas industry for over 40 years, but only recently has its potential as a carbon sequestration method been realized and investigated. Although CO_2 EOR comprises only a small portion of



Schematic of CO_2 EOR

CONTACT POINT:

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Charles Byrer
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-4547
charles.byrer@netl.doe.gov

CUSTOMER SERVICE

1-800-553-7681

NETL WEBSITE

www.netl.doe.gov

all EOR being performed in the U.S., maturing oil fields and narrow profit margins make this method of resource recovery increasingly attractive to industry. The U.S. has been a leader in developing and using technologies for CO_2 EOR; currently about 96% of EOR with CO_2 is preformed in the U.S. A simple schematic of the process is shown on the previous page.

Current CO_2 EOR Operations

Currently, over 8 megatons (Mt: 10^6 Tons) of CO_2 are used for EOR, accounting for 80 percent of all commercially used CO_2 in the U.S. (EIA 2002; DOE 1999). Of this total, about 10 percent (0.8 Mt) is anthropogenic in origin i.e., produced by human activities such as oil refining or fertilizer manufacturing. The rest is extracted from naturally occurring deposits. Up to three-quarters of CO_2 injected stays sequestered, amounting to about 0.6 Mt/year because EOR operator pay a premium price for CO_2 and standard practices recycle its use (Stevens, 2001). The amount of CO_2 that remains sequestered is highly dependent on whether the field is blown-down following any CO_2 operations. Further research and development in this area is expected to improve the storage rate to close to 100 percent. Estimates made by the International Energy Agency (IEA) show that depleted oil wells have the potential to sequester 130 gigatons of Carbon (Gt C: 10^9 Tons C) in total (IEA, 2003).

CO_2 Utilization and Potential in EOR Projects

United States	
Carbon Dioxide use for EOR	8 Mt/yr
• Naturally occurring	7.2 Mt/yr
• Anthropogenic	0.8 Mt/yr
Estimated CO_2 sequestered from EOR operations	0.6 Mt/yr
Worldwide	
Potential CO_2 EOR sequestration	130 Gt C
Total CO_2 accumulated in atmosphere	3-4 Gt C/yr

Benefits

CO_2 EOR is a promising method of sequestration for a number of reasons. First, the geologic structures that originally contained the oil and natural gas should be able to permanently contain the injected CO_2, provided the integrity of the structure is maintained. Because of seismic studies, the geologic structure and physical properties of many oil and gas fields are well understood. This, combined with the vast amount of industry experience with gas-injection EOR, provides a knowledge base from which to start researching the sequestration implications of CO_2 EOR. Another benefit of CO_2 EOR for sequestration purposes is the widespread distribution of depleted and operating oil and gas fields, making it likely that an oil field is near a CO_2 source. Finally, carbon sequestration from CO_2 EOR projects can create offsets resulting in trades in the emerging greenhouse gas market. In February 2002, CO2e.com announced its largest greenhouse gas (GHG) emission reduction trade to date—a transaction between Ontario Power Generation and Bluesource. The forward purchase of 6 million tCO_2 equivalent and option for an additional 3 million tonnes CO_2 equivalent resulted from geologic sequestration projects in Texas, Wyoming, and Mississippi, where CO_2 that would otherwise be vented by natural gas processing plants is used for enhanced oil recovery.

Industries Activities

CO_2 is specifically processed for 62 of the 66 projects utilizing CO_2 for EOR (Stevens, 2001). The CO_2 for these projects is mined from naturally occurring, high-pressure deposits that occur close enough to oil fields to make transmission economically feasible. The following projects, Weyburn and Rangely, are two projects that utilize anthropogenic CO_2 for EOR and additionally promote GHG reduction, since this CO_2 would otherwise be vented to the atmosphere.

Weyburn Project

In October 2000, EnCana began injecting CO_2 into a Williston Basin oilfield (Weyburn) in order to boost oil production. Overall, it is anticipated that some 20 Mt of CO_2 will be permanently sequestered over the lifespan of the project and contribute to the production of at least 122 million barrels of incremental oil from a field that has already produced 335 million barrels since its discovery in 1955. The gas is being supplied via a 205 mile pipeline stretching from the lignite-fueled Dakota Gasification Company Great Plains Synfuels plant site in North Dakota. At the plant, CO_2 is produced from a Rectisol unit in the gas cleanup train of the coal-fired plant. Sales of the CO_2 adds about $30 million of gross revenue to the gasification plant's cash flow each year (additional revenue results from the sale of CO_2; carbon sequestered through this project has not publicly been traded in the greenhouse gas market).

Researchers collected background information prior to the flooding of the field with CO_2, allowing for comparison of field characteristics before and after CO_2 injection and enhancing understanding of interactions and relationships between oil recovery and CO_2 storage.The IEA Weyburn CO_2 Monitoring and Storage Project is coordinated by 20 research organizations in the U.S., UK, France, Italy and Denmark, including the U.S. DOE/NETL Carbon Sequestration Program, and co-administered by the Petroleum Technology Research Centre, Natural Resources Canada, Saskatchewan Industry and Resources, the Saskatchewan Research Council, the University of Regina and IEA GHG. For more information, see The Weyburn Project: A Model for International Collaboration (posted at www.netl.doe.gov/coalpower/sequestration).

Rangely Project

Chevron's Rangely Weber field in Colorado is one of the largest geologic sequestration sites for anthropogenic CO_2. Carbon dioxide for this flood is purchased from the ExxonMobil LaBarge natural gas processing facility in Wyoming and then transported via pipeline to the field. The Rangely CO_2 flood is comprised of an array of 341 production wells and 209 injection wells and extends over an area of 61 km^2. CO_2 injection began at Rangely in 1986 and leakage of CO_2 via wellbores or through the reservoir cap is considered to be negligible. Foams, gels and other strategies are used to improve conformance and reduce premature CO_2 breakthrough. Monitoring wells are used to track movement of injectant within the reservoir, and reservoir simulations estimate ultimate CO_2 sequestration at the Rangely field. By the time the project is completed, an estimated total of 25 Mt (472 Bcf) of CO_2 will have been sequestered.

Summary of Anthropogenic CO2-EOR Projects in the U.S.

Plant Name	Plant Type	CO_2 Supply (t /day)	EOR Field	Operator	Start-up Date
Mitchell, Grey Ranch, Puckett and Terrel	Gas Processing	4.31	SACROC, TX	Pennzoil & Altura	1/1972
LaBarge	Gas Processing	2.58	Rangely, CO	Chevron	10/1986
Enid	Fertilizer	0.60	Purdy, OK	Anadarko	9/1982
Koch	Gas Processing	0.43	Paradis, LA	Texaco	2/1982
Great Plains Synfuels	Gas Processing	16.4	Weyburn, Saskatchewan	EnCana Energy	10/2000

Source: Stevens, 2001 and Moritis, 2002

CARBON SEQUESTRATION THROUGH ENHANCED OIL RECOVERY

Conclusions

CO_2 EOR production will continue to be influenced by oil prices, technological improvements and the development of GHG trading markets, but the use of CO_2 EOR is expected to continue increasing under most future price scenarios. Higher oil prices enhance revenues and profitability. Technologies for improved flood monitoring reduce extraction costs and enhance profitability, stimulating investment and increased production. Emerging GHG markets may provide CO_2 EOR operators with further incentive to use this technique and ensure that CO_2 remains trapped underground. There are a few barriers to implementing CO_2 EOR as a means of sequestration, including:

- Incomplete understanding of reservoir processes
- High costs of capturing, processing, and transporting anthropogenic CO_2, particularly from power generation facilities
- Underdeveloped monitoring and verification technologies
- Unclear emissions trading protocols

These barriers are being addressed through the DOE's Carbon Sequestration Program. For more information about how the research program is specifically addressing CO_2-EOR, you can download The Carbon Sequestration Roadmap and Program Plan and Project Portfolio at www.netl.doe.gov/coalpower/sequestration.

Bibliography:

1. Findsen, Jette; Davies, Christina and Forbes, Sarah. 2003. "Estimating and Reporting GHG Emission Reductions from CO_2 Capture and Storage Activities." Second Annual Conference on Carbon Sequestration, Alexandria, Virginia. May 5-8, 2003.

2. International Energy Agency (IEA). 2003. Greenhouse Gas R&D Programme. Retrieved 1/23/03 from the Internet at http://www.ieagreen.org.uk/.

3. Millennium Energy, Inc. Enhanced Oil Recovery website. Retrieved 1/23/03 from the Internet at http://www.millenniumenergyinc.com/eor.shtml.

4. Moritis, Guntis. 2002. "California Steam EOR Produces Less; Other EOR Continues." *Oil and gas Journal*, v. 100, no. 15, p. 48-74.

5. Moritis, Guntis. 2000. "EOR Weathers Low Oil Prices." *Oil and gas Journal*, v. 98, no. 12, p. 39-61.

6. Stevens, Scott; Kuuskraa, Vello and Gale, John. 2001. "Sequestration of CO_2 in Depleted Oil and Gas Fields: Global Capacity, Costs and Barriers." Advanced Resources International and IEA Greenhouse Gas R&D Programme.

7. U.S. Department of Energy, Energy Information Agency (EIA). December 2002. Emissions of Greenhouse Gases in the United States, 2001.

8. U.S. Department of Energy, Office of Fossil Energy, Office of Science (FE/OS). December 1999. Carbon Sequestration Research and Development.

TERRESTRIAL SEQUESTRATION PROGRAM

Capture and Storage of Carbon in Terrestrial Ecosystems

CONTACT POINTS

John T. Litynski
Terrestrial Program Coordinator
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-1339
304-285-4469 fax
john.litynski@netl.doe.gov

Scott M. Klara
Sequestration Product Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

CUSTOMER SERVICE

800-553-7681

WEBSITE

www.netl.doe.gov

Background

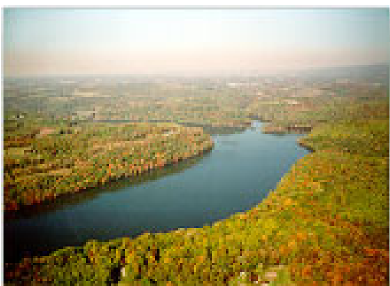
Clean, affordable energy is essential for U.S. prosperity and security in the 21st century. Over half of the electricity in the U.S. currently comes from coal-fired boilers, with coal projected to account for over half of U.S. electricity generation through 2020 and beyond. From a global perspective, in developing nations coal use for electricity generation is projected to more than double by 2020. This continuing demand for fossil-fuel-based power and the associated rise in atmospheric carbon dioxide (CO_2) concentrations will require innovative ways to capture and store carbon.

Terrestrial ecosystems, which include both soil and vegetation, are widely recognized as a major biological “scrubber” for CO_2. Terrestrial sequestration is defined as either the net removal of CO_2 from the atmosphere or the prevention of CO_2 emissions from leaving terrestrial ecosystems. Sequestration can be enhanced in four ways: reversing land use patterns; reducing the decomposition of organic matter; increasing the photosynthetic carbon fixation of trees and other vegetation; and creating energy offsets using biomass for fuels and other products. The terrestrial biosphere is estimated to sequester large amounts of carbon, about 2 billion tons (2 Gt) of carbon annually. The total amount of carbon stored in soils and vegetation throughout the world is estimated to be about 2,000 Gt +/- 500.

CONCURRENT BENEFITS

Terrestrial sequestration also offers significant additional benefits including:

- Creating wildlife habitat and green space
- Preventing soil erosion and stream sedimentation
- Boosting local and regional economies
- Reclaiming poorly managed lands
- Increasing recreational value of lands



Program Goal

"To provide economically competitive and environmentally safe options for offsetting the projected growth in CO_2 emissions."

Description

The U.S. Department of Energy's Office of Fossil Energy (FE) and Office of Science are jointly carrying out research on the capture and storage of carbon in terrestrial ecosystems. FE's current activities, which are managed by the National Energy Technology Laboratory (NETL), focus on enhancing the productivity of terrestrial ecosystems through the application of soil amendments, such as coal-combustion byproducts and biosolids produced at wastewater treatment facilities. The goal of the program is to provide economically competitive and environmentally safe options for offsetting the projected growth in CO_2 emissions. The cost of the options is in the range of $10/ton of avoided net costs for sequestration. The efforts are based on fostering partnerships between landowners, biomass and biofuels industry representatives, government agencies, and energy producers, such as coal companies and utilities. This partnering will help to determine the best approaches for increasing the amount of carbon sequestered in soils and vegetation.

Project Summaries

Applied Terrestrial Sequestration Partnership

The Applied Terrestrial Sequestration Partnership, an integrated research program led by Los Alamos National Laboratory (LANL)and NETL, is taking a leading role in developing breakthrough technologies and applications for terrestrial carbon sequestration.

Ecosystem Dynamics Understanding both ecosystem dynamics and economic issues is critical to the success of terrestrial sequestration as a policy option. Marginal lands (forest, farm, range, or industrial) can serve as a barometer for climate change and are ideal field sites for investigating terrestrial sequestration. This study uses a multi-disciplinary approach, integrating lab and field studies with the CENTURY model. The result will be a fundamental understanding of how changes in the plant community are reflected in carbon inventories and a detailed economic analysis of carbon sequestration in reclamation sites.

Advanced Plant Growth The research team, including partners at the Ohio State University, the University of Southern Maine, the National Energy Technology Laboratory, and the University of California at San Louis Obispo uses plant metabolites to optimize terrestrial carbon sequestration at reclamation sites. Metabolites will increase plant growth rates, biomass volume, and carbon dioxide uptake–maximizing sequestration potential. DNA-based methods are being used to fingerprint soil bacterial and identify their role in nutrient recycling. Field studies assess microbial response to changing water and temperature conditions.

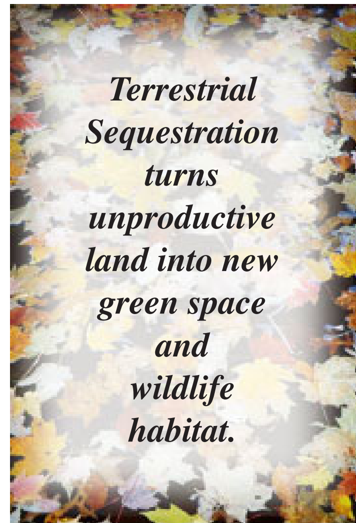
Soil Carbon Measurements An integrated research team is working to develop new field-deployable, laser-based instruments for measurement and characterization of soil carbon. These instruments will revolutionize the practice of soil carbon science and allow for a more accurate accounting for terrestrial carbon sequestration. Instruments will be calibrated to a wide variety of soils and tested in the field. Results will be compared with traditional carbon measurements with respect to accuracy, cost, and time.

Enhancing Carbon Sequestration and Reclamation of Degraded Lands with Fossil Fuel Combustion Systems

Oak Ridge National Laboratory (ORNL) and Pacific Northwest National Laboratory (PNNL) are teaming with Ohio State University and Virginia Polytechnic Institute to determine the best way to increase the carbon sequestration potential of land previously disturbed by mining, highway construction, or poor land management practices. The team will focus on the use of amendments derived from paper production, biological waste treatment facilities, and solid byproducts from fossil-fuel combustion to identify and quantify the key factors necessary for the successful reclamation of degraded lands. The results will be summarized in a set of guidelines containing practical information about matching amendment combinations to land types and optimum site-management practices. Long-term field studies will be designed and site(s) recommended for the demonstration and further optimization. (ORNL and PNNL are part of DOE's Center for Enhancing Carbon Sequestration in Terrestrial Ecosystems [CSiTE] which is run by the DOE Office of Science.)

Carbon Capture and Water Emissions Treatment System at Fossil-Fueled Electric Generating Plants

The Tennessee Valley Authority and EPRI are partnering to demonstrate and assess the life-cycle costs of integrating electricity production with enhanced terrestrial carbon sequestration. The project is being conducted on coalmine spoil land at the 2,558 megawatt (MW) Paradise Station (Kentucky). This station, which burns bituminous coal and is currently equipped with flue gas desulfurization (FGD) for SO_2 control and is set to begin using selective catalytic reduction for NO_x control, will use the byproducts from these control systems to amend the mine soils. Treated water generated by the FGD system will be used to irrigate the soils. Benefits include: use CCBs to improve reclamation sites and carbon sequestration, development of a passive technology for criteria pollutant release reduction in water, development of a wildlife habitat and green space, generation of Total Maximum Daily Load (TMDL) credits for water and airborne nitrogen, and development of additional forest lands.



Enhancement of Terrestrial Carbon Sinks through Reclamation of Abandoned Mine Lands in the Appalachian Region

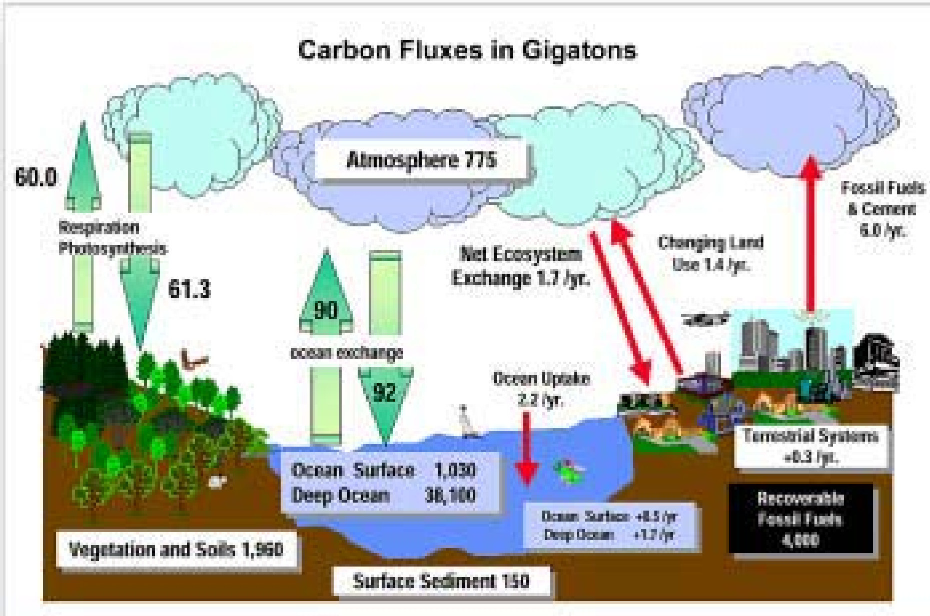
Stephen F. Austin State University, working with TXU (Texas Utilities) and Westvaco, is investigating storing carbon in trees on abandoned mine lands in the Appalachian region. Researchers are studying the potential for reclamation and reforestation and the development of a free-trade system for carbon credits. The focus is on developing an environmentally safe way to use mined lands and accomplish long-term carbon sequestration. Growth and yield models will be applied to commercial tree species in order to quantify the maximum amount of carbon that can be stored. Discounted cash-flow analyses will be conducted and the soil expectation value will be calculated to predict the per ton cost of carbon sequestration. A "carbon credit" market between landowners and utility and coal companies will be investigated, as well as analysis of the impact of sequestration on the local economy.

Application and Development of Appropriate Tools and Technologies for Cost-effective Carbon Sequestration

The Nature Conservancy will be working in close collaboration with U.S. based companies (including General Motors and American Electric Power) and NGO partners to study how carbon dioxide can be stored more effectively by changing land use practices and investing in forestry projects. The project will focus on gaining cost-effective, verified measurements of the long-term potential of various carbon sequestration and land use emissions avoidance strategies. The project will use newly developed aerial and satellite-based technology to study forestry projects in Brazil and Belize to determine their carbon sequestration potential, and will also test new software models to predict how soil and vegetation store carbon at sites in the United States and abroad.

Terrestrial Sequestration Program

Capture and Storage of Carbon in Terrestrial Ecosystems



PARTICIPANTS

American Electric Power (AEP)
Columbus, Ohio

EPRI
Palo Alto, California

GM
Detroit, Michigan

Los Alamos National Laboratory
Los Alamos, New Mexico

Oak Ridge National Laboratory
Oak Ridge, Tennessee

Ohio State University
Columbus, Ohio

Pacific Northwest National Laboratory
Richland, Washington

Savannah River
Savannah River, Georgia

Stephen F. Austin State University
Nacogdoches, Texas

Tennessee Valley Authority
Chattanooga, Tennessee

TXU (Texas Utilities)
Dallas, Texas

US Department of Agriculture Forest Service
Charleston, South Carolina

US Department of Interior Office of Surface Mining
Washington, DC

US Department of Energy Office of Science
Washington, DC

Virginia Polytechnic Institute
Blacksburg, Virginia

Westvaco
New York, New York

The Global Carbon Cycle

The figure above presents a simplified version of the global carbon cycle. The large arrows represent natural paths of carbon exchange and the small arrows represent the human or anthropogenic contributions to the carbon cycle. The flow of carbon is measured in billions of metric tons (gigatons).

The locations where carbon is stored are called “sinks.”

These carbon “sinks” are immense. The atmosphere contains about 750 billion metric tons of carbon dioxide, the ground contains about 2,190 billion metric tons of carbon dioxide, and the oceans contain about 40,000 billion metric tons of carbon dioxide.

The arrows show the yearly exchange between these sinks. Plants and soils “give” about 60.0 billion metric tons of carbon dioxide to the atmosphere and “take” about 61.3 billion metric tons of carbon dioxide. The difference is the ability of green plants to “fix” carbon by photosynthesis.

The ocean absorbs 92 billion metric tons of carbon dioxide, which is slightly more than the 90 billion metric tons of carbon dioxide that is absorbed by the water. These are the main “fluxes” or flows of carbon that occur in nature.

The anthropogenic flux of carbon comes from two major sources. The larger of the two is from the burning of fossil fuels for electricity and cement production at 5.5 billion metric tons of carbon per year that is released to the atmosphere. The smaller of the two is the exchange of this carbon dioxide from land use changes that results in 1.4 billion metric tons of carbon dioxide being released to the atmosphere. 1.7 billion metric tons of carbon dioxide is absorbed by the land, resulting in a net exchange of +0.3 billion metric tons per year.

PROGRAM facts

U.S. Department of Energy
National Energy Technology Laboratory

Sequestration

10/2002

CONTACT POINTS

Scott M. Klara
Sequestration Product Manager
412-386-4864
scott.klara@netl.doe.gov

Perry Bergman
Project Manager
Environmental Projects Division
412-386-4890
perry.bergman@netl.doe.gov

ADDRESS

National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236-0940

PARTNERS

Research Institute for Innovative Technology for the Earth (RITE)
Japan

The Norwegian Institute for Water Research
Niva, Norway

The Institute of Ocean Science
Ios, Canada

The Commonwealth Scientific and Industrial Research Organization (CSIRO)
Australia

CUSTOMER SERVICE

800-553-7681

WEBSITE

www.netl.doe.gov

Sequestration of Carbon Dioxide Emissions in the Ocean

Description

The world's oceans represent the largest potential sink for the carbon dioxide (CO_2) produced by human activities. Already oceans contain the equivalent of an estimated 140,000 gigatons of CO_2. The ocean's natural carbon transfer processes have spans of thousands of years and will eventually transfer 80-90 percent of today's man-made (anthropogenic) CO_2 emissions to the deep ocean. This natural CO_2 transfer may already be adversely affecting marine life near the ocean and could also be altering deep ocean circulation patterns.

The effectiveness of ocean storage techniques depends largely on how long the CO_2 would remain in the ocean. Most studies indicate that if CO_2 can be injected into deep oceanic water circulation, it will remain there for approximately 1000 years.

Direct injection of CO_2 into the ocean would reduce both atmospheric CO_2 concentrations and their sharp rate of increase. The purpose of this program is to investigate the technical, economic and environmental feasibility of CO_2 sequestration in the deep ocean, primarily by deep injection.

Projects

Feasibility of Large Scale Ocean Sequestration: Experiments on the Ocean Disposal of Fossil Fuel CO_2

Monterey Bay Aquarium Research Institute will use the Remotely Operated Vehicle (ROV) to carry out pilot experiments involving the deployment of small quantities of liquid CO_2 in the deep ocean for the purposes of investigating the fundamental science underlying concepts of ocean CO_2 sequestration. Below a depth of about 3000m the density of liquid CO_2 exceeds that of seawater, and the liquid CO_2 is quickly converted into a solid hydrate by reacting with the surrounding water.

Feasibility of Large Scale Ocean Sequestration: Optimized In Site Raman Spectroscopy on the Sea Floor and Effects of Clathrate Hydrates on Sediment

The research group at Washington University in St. Louis will work with MBARI to carry out the first direct in situ analysis on the seafloor of CO_2 clathrate hydrates, their entrained and surrounding fluids, along with sediments adjacent to the clathrate hydrates, using a Raman spectrometer. This information on the physical chemical of clathrate hydrates and clathrate sediment interaction is essential for the evaluation of CO_2 ocean sequestration.

Sequestration of Carbon Dioxide Emissions in the Ocean

PROJECTS

Feasibility of Large-Scale Ocean CO_2 Sequestration: Experiments on the Ocean Disposal of Fossil Fuel CO_2
Principal Investigator:
Dr. Peter Brewer, 831-775-1706
Partner: Monterey Bay Aquarium Research Institute

Feasibility of Large-Scale Ocean CO_2 Sequestration: Optimized in Situ Raman Spectroscopy on the Seafloor and Effects of Clathrate Hydrate on Sediment
Principal Investigator:
Prof. Jill Pasteris,
316-935-5889
Partner: University of Washington at St. Louis

Accelerated Carbonate Dissolution as CO_2 Capture and Sequestration Strategies
Principal Investigator:
Terry Surles, 925-423-1615
Partners: Lawrence Livermore National Laboratory (LLNL), and U.S. Geological Survey (USGS)

Large Scale CO_2 Transportation and Deep Ocean Sequestration
Principal Investigator:
Hamid Sarv, 330-821-9110
Partners: McDermott Technology, Inc., and University of Hawaii

Ocean Carbon Sequestration
Principal Investigator:
Rick Coffin, 202-767-0065
Partner: Naval Research Laboratory

International Collaboration Project on CO_2 Sequestration
Principal Investigator:
Howard Herzog, 617-253-0688

Public Outreach and Permitting
Principal Investigator:
Gerard Nihous, 808-539-3874
Partner: Pacific International Center for High Technology Research (PICHTR)

Accelerated Carbonated Dissolution as CO_2 Capture and Sequestration Strategy

Lawrence Livermore National Laboratory and the U.S. Geological Survey will conduct a laboratory program to synthesize and study the physical properties of CO_2 hydrates, and will contrast these properties of methane hydrates. Gas-solid exchange experiments will methane hydrates to determine whether methane extraction from natural gas and CO_2 sequestration can be accomplished in a single step.

Large Scale CO_2 Transportation and Deep Ocean Sequestration

The objective of the project is to investigate the techno-economic viability of large-scale carbon dioxide transportation and deep ocean sequestration. Two cases are being investigated; one involving ocean tanker transport of liquid CO_2 to an offshore floating platform on a barge with vertical injection to the ocean floor and the other involving transporting liquid CO_2 through undersea pipelines to the bottom of the ocean.

Ocean Carbon Sequestration

The objective of this project is to provide logistical and technical support for the International Collaboration Project on CO_2 Ocean Sequestration. Such support includes providing a surface vessel for the project, biological experiments and a survey of potential test sites.

International collaboration Project on CO_2 Ocean Sequestration

The objective of this project is to develop instrumentation and potential experiments for the International Project on CO_2 Ocean Sequestration. This international effort involves four nations (United States, Japan, Norway, and Canada) and one private corporation, CABB of Switzerland. The field experiment is scheduled to take place in the summer of the year 2001, at Keahole Point on the Kana Coast off the big island of Hawaii.

Public Outreach and Permitting

The objective of this project is to conduct the public outreach and permitting activities associated with the International Project on CO_2 Ocean Sequestration. This effort although primarily conducted on the large island of Hawaii, is also being carried out within the state of Hawaii and on the continental United States.

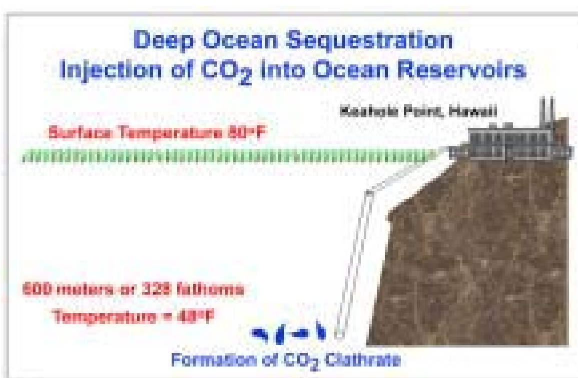


Figure 1 presents the basic idea of ocean based sequestration. While the surface of the ocean (near Hawaii) is at the perfect temperature of 80 degrees F for a vacation, the temperature at 600 meters is a cold 48 degrees Fahrenheit. Water pressure increases with depth and at 600 meter below the surface, the water pressure is sufficient to keep CO_2 in the liquid or solid state.

PROGRAM **facts**

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

Sequestration

03/2005

Field Tests Demonstrate Secure CO_2 Storage in Underground Formations

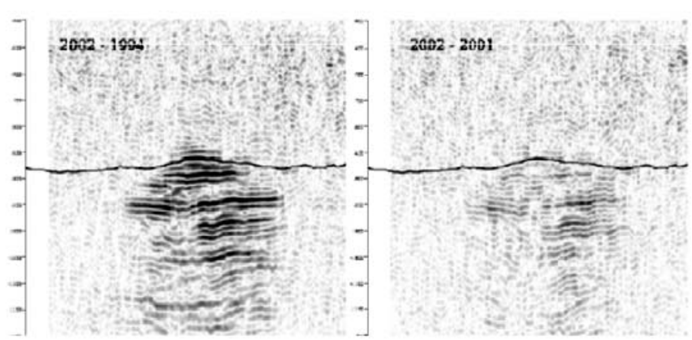
The option of sequestering carbon dioxide (CO_2) in underground geologic formations has received a huge boost from two industry-led commercial-scale storage projects: the Sleipner project off the coast of Norway and the Weyburn project in Ontario Canada. Through collaborative efforts, the United States Department of Energy is involved in both projects, primarily in the role of providing more rigorous monitoring of the injected CO_2 and studying its behavior to a greater extent than the project operators would have pursued on their own – a mutually beneficial public/private partnership.

The key result from both field projects is that no CO_2 *leakage has been observed nor is there any indication that* CO_2 *will leak in the future.* The projects are summarized as follows.

Sleipner Statoil's Sleipner field in the Norwegian North Sea is a large producer of natural gas. The natural gas reservoir is deep, 3,500 meters below the sea floor, and the natural gas produced contains 9% CO_2. CO_2 must be reduced to 2.5% for sale into a pipeline, and Statoil operates a natural gas processing platform in which CO_2 is scrubbed with amine absorbents.

Above the Sleipner natural gas reservoir, at 1,000 feet below the seabed is a large porous sandstone formation with a shale cap rock, the Utsira formation. It is an ideal setting, and Statoil decided to go forward with plans to capture CO_2 from the natural gas processing platform and inject it into the Utsira. Scientists estimate the Utsira has the capacity to store 600 billion tons of CO_2, and to date over 6 million tons of CO_2 have been injected.

Formerly the scrubbed CO_2 was vented to the atmosphere. However, a CO_2 emissions tax levied by the Norwegian government motivated Statoil to consider capturing the vented CO_2, compressing it, and injecting it underground.



3D Seismic conducted at the Sliepner Field show a bright CO_2 *signature and no leakage above the Utsira formation.*

CONTACTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Sarah Forbes
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-4670
sarah.forbes@netl.doe.gov

National Energy Technology Laboratory

626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236-0940
412-386-4687

3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880
304-285-4764

One West Third Street, Suite 1400
Tulsa, OK 74103-3519
918-699-2000

P.O. Box 750172
539 Duckering Bldg./UAF Campus
Fairbanks, AK 99775-0172
907-452-2559

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

The flow of CO_2 in the Utsira has been monitored primarily using time-lapse seismic technology, in which scientists take a seismic snapshot of a formation before and after injection and study the differences. CO_2 is more compressible than brine and sound waves travel through it at a different velocity. Thus CO_2 in a saline formation leaves a bright signature. The time lapse seismic results shown in the figure indicate that there is no migration of CO_2 out of the Utsira[1].

Weyburn

The Weyburn oil field in Saskatchewan Canada was discovered in 1954 and reached a peak crude oil production of 50,000 barrels per day in 1967. In 1997 EnCana announced that it would develop a CO_2 enhanced oil recovery project with the goal of extending the life of the Weyburn field by more than 25 years and extracting an additional 122 million barrels of crude oil.

Encana solicited proposals for CO_2 supply from anthropogenic sources. Dakota Gasification Co., operator of the Great Plains Synfuels plant in Beulah, North Dakota, submitted the winning proposal. Dakota Gasification offered to build a 325-km pipeline between Buela and Weyburn with a capacity to supply at least 2.7 million m^3/day of CO_2. As of May 2003, cumulative CO_2 injected was 3.5 million metric tons. It is planned that 20 million tons of CO_2 will be injected over the life of the project.

Petroleum Technology Research Center (PTRC) initiated a research project to operate in parallel with the commercial oil recovery project [2]. The goals of the research project are to develop a rigorous baseline of the formation, to use the CO_2 flood as an opportunity to gain understanding of the behavior of injected CO_2, to field test a range of CO_2 monitoring technologies, and to develop the ability to model and predict the flow of CO_2 in an underground formation over long periods of time. The U.S. Department of Energy co-funded the research project which was managed by the National Energy Technology Laboratory.

A wide range of CO_2 measurement and monitoring approaches were tested at the Weyburn site including observation wells, 3D seismic, cross-well seismic, soil monitors, and gas tracers. Researchers predict they can use 3D seismic to detect volumes of CO_2 as small 2,500 metric tons. Soil sampling indicates no leakage of CO_2 from the reservoir. There are some anomalies in the seismic readings in the overlying formations which prevent the investigators from making definitive statements regarding the seismic results, but there is “no independent evidence to suggest any significant volume of CO_2 has migrated above the reservoir.”

References:

[1] Arts, et al., 2004 “Recent Time-Lapse Seismic Data Show No Indication of Leakage at the Sleipner CO_2 Injection Site” presented at the 7th International Conference of Greenhouse Gas Control Technologies (GHGT-7)

[2] M. Monea and M. Wilson, 2004, “IEA GHG Weyburn CO2 Monitoring & Storage Project Summary Report 2000-2004,” from the proceedings of GHGT-7

PROGRAM facts

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

Sequestration

03/2005

CONTACTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Sarah Forbes
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-4670
sarah.forbes@netl.doe.gov

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

The Cost of Carbon Dioxide Capture and Storage in Geologic Formations

Sequestration of carbon dioxide (CO_2) in geologic formations is tendered as an option for achieving deep reductions in greenhouse emissions without hindering economic prosperity. Strong interest in the concept speaks to the usefulness and abundance of fossil fuels compared to other energy sources. But cost is a key issue. The volume of carbon dioxide emitted from power plants and other energy systems is enormous compared to other emissions of concern. For example, a pulverized coal boiler operating on Kentucky coal (2.5% sulfur) may generate 0.03 lbs of sulfur dioxide per kWh and emit CO_2 at a rate of 1.7 pounds per kWh.

The United States Department of Energy's Carbon Sequestration Program has set forth two overarching cost goals for its research portfolio: CO_2 capture technologies for a pulverized coal plant should achieve 90% CO_2 capture and increase the cost of electricity no more than 20%. And CO_2 capture technologies for coal gasification should increase the cost of CO_2 capture should achieve 90% capture and increase COE by no more than 10%. The National Energy Technology Laboratory has conducted systems analyses to estimate the cost of CO_2 capture and sequestration using a range of technologies. DOE has partnered with a number of respected engineering firms in the conduct of the work, including EPRI, Alstom Power, Air Liquide, SFA Pacific and Parsons. Every effort has been made to use real-world data where possible and to incorporate appropriate contingencies into the cost estimates.

The attached table presents a compendium of results from several DOE-funded studies. The data represent a full life cycle cost in that CO_2, capture, transport, and storage are included in the total cost. Several observations can be drawn:

- The cost of electricity (COE) from coal-fired power plant with 90% CO_2 capture ranges from roughly 6-9 cents/kWh in the near term, decreasing with a successful technology development effort, to roughly 5-7 cents/kWh in the 2010-2025 time frame. Although these costs can be viewed as encouraging under a worst-case scenario of GHG emissions constraints, they fall short of the program goals and call for a robust research and development effort. Note that the chemical looping technologies that best approach the goals entail a significant amount of technical risk, and the economics of the ammonia scrubbing system rely on revenues from by-product fertilizer.

National Energy Technology Laboratory

626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236-0940
412-386-4687

3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880
304-285-4764

One West Third Street, Suite 1400
Tulsa, OK 74103-3519
918-699-2000

P.O. Box 750172
539 Duckering Bldg./UAF Campus
Fairbanks, AK 99775-0172
907-452-2559

- The cost of CO_2 emissions avoided associated with CO_2 capture from a coal-fired power plant ranges from 50-200 $/ton CO_2 with current technology. It decreases to 30-140 $/ton CO_2 in the 2010-2025 time frame with a successful technology development effort. The cost of CO_2 emissions avoided decreases more significantly that does COE because advanced technology power plants are more efficient.

- For the cases presented, CO_2 capture represents between 93% and 95% of the total cost of capture, transport, and storage. This is consistent with recent work by Sally Benson et al. indicating the cost of monitoring and verification of stored CO_2 is relatively small (16-31cents per ton of CO_2 stored). This result should not be interpreted as a basis for a lower priority for CO_2 storage and MM&V research. These areas face significant performance challenges even though the estimated costs are not prohibitive; they are also essential for building public acceptance of sequestration technologies and ensuring safety.

Table 1. Estimates of the Cost of CO2 Capture from Coal-fired Power Plants and Sequestration in Geologic Formations

		Pulverized Coal					Coal Gasification				
		2005-2010			2010-2025		2005-2010			2010-2025	
		A[1]	B[1]	C[5]	D[4]	E[3]	F[4]	G[2]	H[6]	I[6]	J[4]
Capture	COE (c/kWh)	8.88	7.49	5.90	7.69	7.5	5.84	6.3	6.0	5.4	5.22
	% h in COE	75	44	13	47	44	12	29	23	11	6
	$/ton CO2 avoid.	55	31	10	30	31	11	21	16	7	3
	$/ton Carbon avoid.	194	114	34	99	114	40	74	58	27	11
Trans-port/store	COE (c/kWh)	0.46	0.40	0.40	0.33	0.40	0.33	0.40	0.39	0.37	0.33
	$/ton CO2 avoid.	6.3	5.7	5.7	4.4	5.7	4.4	6	5.4	5.2	4.4
	$/ton C avoid.	23	21	21	16	21	16	22	20	19	16
Transported 50 miles; stored in Saline Formation 1,500ft.											
TOTAL	COE (c/kWh)	9.34	7.89	6.3	8.02	7.90	6.17	6.7	6.39	5.79	5.55
	% h in COE	84	51	16	54	51	18	37	31	18	13
	$/ton CO2 avoid.	61	37	16	31	37	15	26	21	13	7
	$/ton C avoid.	217	135	55	115	135	56	96	78	46	27
	Efficiency (%)	28	31	31	30	28	31	36	37	39	37
	Energy Penalty (%)	18	16	16	19	18	16	13	8	2.6	8

A—Supercritical w/MEA Scrubbing
B—Ultra-supercritical w/advanced MEA Scrubbing
C—Ammonia Scrubbing
D—Oxy-fuel-CMB with O2 Membrane
E—Oxy-fuel PC Combustion
F—CMB Chemical Looping Comb.
G—Selexol Scrubbing
H—Advanced Selexol & Co-Storage H2S
I—Adv. Selexol + Co-Storage H2S + WGS and O2 Membranes
J—Chemical Looping Gasification
K—Gasification Chemical Looping

References:

1. EPRI/DOE Technical Report 1000316, "Evaluation of Innovative Fossil Fuel Power Plants with CO2 Removal", December 2000
2. EPRI/DOE Technical Report 1004483, "Updated Cost and Performance Estimates for Fossil Fuel Power Plants with CO2 Removal", December 2002
3. AirLiquide/DOE Technical Report DE-FC26-02NT41586, "Advanced, Low/Zero Emission Boiler Design and Operation", November, 2004
4. ALSTOM/DOE Technical Report DE-FC-01NT41146, "Greenhouse Gas Emissions Control by Oxygen Firing in Circulating Fluidized Bed Boilers", May 2003
5. Ciferno, J., DiPietro, P., Tarka,T., "An Economic Scoping Study for CO2 Capture using Aqueous Ammonia", November, 2004
6. Estimated using the NETL Carbon Sequestration Economic Model

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

Sequestration

03/2005

LAKE NYOS AND MAMMOTH MOUNTAIN: WHAT DO THEY TELL US ABOUT THE SECURITY OF ENGINEERED STORAGE OF CO_2 UNDERGROUND?

CONTACTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Sarah Forbes
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-4670
sarah.forbes@netl.doe.gov

Introduction

Lake Nyos in Western Africa and Mammoth Mountain in California are two well-known underground releases of carbon dioxide (CO_2) in nature, both with adverse effects. Both Lake Nyos and Mammoth Mountain are atop current or former volcanoes and the released CO_2 is volcanic in origin (sometimes referred to as Magmatic Origin). Molten rock (magma) far below the Earth's surface contains entrained amounts of water, carbon dioxide, and other gases. If the magma rises toward the Earth's surface, the pressure it is under is reduced and the entrained gases begin to expand. The expansion of the entrained gases forces the magma to move faster in a spiraling effect. In fact, it is the force of expanded gases that give volcanoes most of their power. Water vapor is the primary volcanic gas, but CO_2 can account for nearly half the entrained gas in certain formations. Worldwide, volcanoes release 130 million tons of CO_2 into the Earth's atmosphere.

This document discusses these incidences and evaluates their implications for engineered CO_2 storage in underground formations, i.e., geologic sequestration. In summary, all hazardous releases of CO_2 from the earth — such as Lake Nyos and Mammoth Mountain — are associated with CO_2 release from magma held deep within the earth's crust. Although much can be learned from Lake Nyos and Mammoth Mountain regarding large releases of CO_2 into the atmosphere, these situations have little relevance to potential CO_2 release from engineered storage of CO_2 in geologic formations. No known hazardous CO_2 leaks have ever been associated with leakage from a geologic formation.

Lake Nyos

Controlled degassing of Lake Nyos will prevent a second catastrophic CO_2 release

Located in the west-African country of Cameroon, Lake Nyos is a few square kilometers in area and 200 meters (m) deep. It is situated in the crater formed from the collapse of the rock channel feeding a now extinct volcano. The lake is compositionally stratified, with fresh water in the upper 50 m and heavier sodium and carbon dioxide rich water below that. The water below 180 m is particularly rich in sodium and carbon dioxide. Most of the sodium and carbon dioxide come from numerous sodium-bicarbonate bearing springs - derived from an underlying magma chamber - feeding into the bottom of the lake.

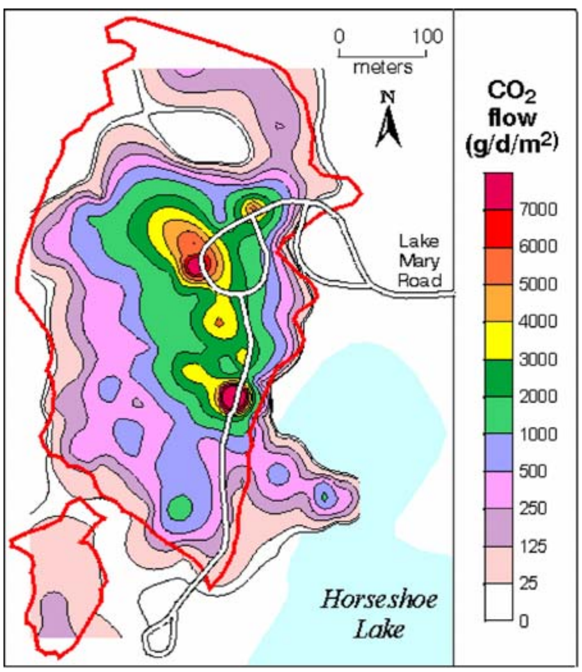
In August of 1986 some event – perhaps a mudslide, heavy rain or wind blowing across the lake – caused the water column to be disturbed. Some of the deep carbon dioxide rich water moved towards surface where it was subjected to lower pressure. The dissolved carbon dioxide quickly converted to carbon dioxide gas and rushed to the surface starting a chain reaction of degassing the deeper water. A huge cloud of carbon dioxide spilled over the lake's outlet and down into the surrounding valleys. Thousands of animals and 1700 people died, many in their sleep.

The lake is now degassed in a controlled way to prevent a reoccurrence. The procedure involves lowering a strong polyethylene pipe to the lake bottom. Some water is pumped out at the top, and as the deep water rises through the pipe the carbon dioxide starts to bubble out. The gas and water then become buoyant and suck more water in at the bottom in a self-sustaining process.
http://www.mala.bc.ca/~earles/nyos-feb01.htm

Mammoth Mountain

Numerous small earthquakes occurred beneath Mammoth Mountain in California USA between May and November of 1989. Data collected from monitoring instruments during those months indicated that a small body of magma was rising through a fissure beneath the mountain. In the following year, U.S. Forest Service rangers noticed areas of dead and dying trees on the mountain. After drought and insect infestations were eliminated as causes, USGS scientists discovered that the roots of the trees were being killed by exceptionally high concentrations of CO_2 gas in the soil. Although trees produce oxygen (O_2) from CO_2 during photosynthesis, their roots need to absorb O_2 directly. High CO_2 concentrations in the soil kill plants by denying their roots O_2 and by interfering with nutrient uptake. In the areas of tree kill at Mammoth Mountain, CO_2 makes up about 20 to 95% of the gas content of the soil; there is less than 1 percent CO_2 in soils outside the tree-kill areas. Today areas of dead and dying trees at Mammoth Mountain total more than 170 acres, with a total CO_2 flux of roughly 300 tons per day.

The events at Lake Nyos and Mammoth Mountain do provide examples of "lessons learned" regarding release of extremely high concentrations of CO_2.



CO_2 flowrates in the area around Mammoth Mountain, CA; tree kill area shown by the red outline. Data from 1999
http://lvo.wr.usgs.gov/CO2.html

Implications for Underground CO_2 Storage

National Energy Technology Laboratory

626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236-0940
412-386-4687

3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880
304-285-4764

One West Third Street, Suite 1400
Tulsa, OK 74103-3519
918-699-2000

P.O. Box 750172
539 Duckering Bldg./UAF Campus
Fairbanks, AK 99775-0172
907-452-2559

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

All hazardous releases of CO_2 from the earth—such as Lake Nyos and Mammoth Mountain—are associated with volcanism. No known hazardous CO_2 leaks have ever been associated with leakage from a geologic formation. The events at Lake Nyos and Mammoth Mountain do provide examples of "lessons learned" regarding release of extremely high concentrations of CO_2. CO_2 is buoyant underground and will, under the right circumstances, rise from underground strata and into the atmosphere. Once is in the atmosphere, CO_2 is relatively heavy and can gather temporarily in low-lying areas and confined spaces. Because CO_2 is an asphyxiant, high CO_2 concentrations in the soil will destroy plants and CO_2 concentrations in the air higher than 30 volume percent are fatal to humans within minutes.

Mammoth Mountain shows us that even relatively high flux rates through the soil do not result in high-risk asphyxiation hazards for humans and animals. People still use Mammoth Mountain for recreation, but are advised not to lie face down on the ground in the tree kill areas. Also trees and other foliage will often serve as a "canary in a coal mine," alerting people of potential risks before they materialize.

Engineered sequestration projects are and will be preformed only under optimal circumstances —and pre-, during, and post-injection monitoring plans will be implemented. Every project will perform a high level of due diligence activities related to reservoir characterization and monitoring leakage. The likelihood that any stored CO_2 will escape from the target formation will be very low. A large portion of any CO_2 that does escape will often be dissolved or trapped in the strata that lie above the injection site, prior to reaching the surface. Underground monitoring technologies such as 3D seismic will give operators years or even decades of advanced notice that CO_2 could escape the target formations. Geologic sequestration poses no additional risks beyond the daily risks currently associated with CO_2 injection in the oil and gas industries. Over 70 CO_2 enhanced oil recovery projects inject more than 8 million tons of CO_2 per year into oil reservoirs throughout the United States and Canada. Many of these projects have been injecting at these levels for more than 20 years. Numerous projects also exist for enhanced coalbed methane recovery using CO_2 injection and acid gas disposal injection containing high quantities of CO_2 and H_2S into geologic formations. The Sleipnor Gas Field in the North Sea is an example of CO_2 injection into a saline formation specifically for sequestration purposes. This project has been injecting over 1 million tons of CO_2 per year since 1996. All of these projects continue to operate in a safe, effective manner with a low level of environmental safety & health risk. The risk of large, catastrophic releases of CO_2, such as Lake Nyos and Mammoth Mountain, are virtually non-existent for geologic sequestration.

PROGRAM
facts

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

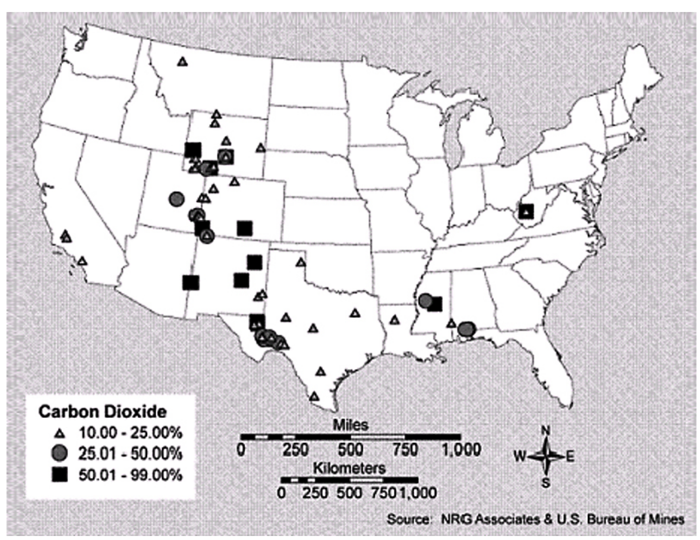
Sequestration

03/2005

RISK ASSESSMENT FOR LONG-TERM STORAGE OF CO_2 IN GEOLOGIC FORMATIONS

The aim of geologic sequestration is to identify and properly utilize formations that will store CO_2 securely — in much the same way as underground formations have stored oil and natural gas for hundreds of millions of years. Yet CO_2 in an underground formation is buoyant and exhibits low viscosity. If unconstrained, it will flow upwards through rock pores and channels until it reaches the atmosphere. Thus there is a fundamental risk of CO_2 escape, particularly low seepage of CO_2 from a storage reservoir. Although highly improbable, large releases of CO_2 are theoretically possible and risk assessment approaches must address this remote possibility. Large scale releases that escape via a fast pathway may damage trees and other plants via elevated concentrations of CO_2 in soil, present asphyxiation hazards through pooling of CO_2 in low-lying areas and confined spaces, and possibly be harmful to drinking water supplies. Risk assessment must be designed to account for all of these possibilities.

The United States Department of Energy's Office of Fossil Energy has developed a clear vision for the safe and environmentally sound operation and management of geologic CO_2 storage facilities over the long term. This vision is rooted in a science-based technology development effort aimed at fully understanding and effectively managing the risks associated with CO_2 storage. The Department's Sequestration Program has a risk assessment R&D component called "Monitoring, Mitigation, and Verification (MM&V). MM&V is defined as the capability to measure the amount of CO_2 stored at a specific sequestration site, monitor the site for leaks or other deterioration of storage integrity over time, and to verify that the CO_2 is stored in a



Scientists are studying natural underground deposits of CO_2 to better understand factors affecting storage permanence. The map above shows the locations of geologic formations in the United States that have contained natural deposits of CO_2 for millions of years.

CONTACTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Sarah Forbes
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-4670
sarah.forbes@netl.doe.gov

The aim of geologic sequestration is to identify and properly utilize formations that will store CO_2 securely.

way that is permanent and not harmful to the host ecosystem. Mitigation capability will provide a response to CO_2 leakage or ecological damage in the unlikely event that it should occur. It is likely that all large scale sequestration deployments will have a mitigation plan in place before operations begin.

MM&V standards and protocols are being developed to ensure permanence, to ensure that the risk of any leakage is minimal, and should it occur, leakage can be safely mitigated. MM&V can be broken into three broad categories: Subsurface, Soils, and Above-ground. Subsurface MM&V involves tracking the fate of the CO_2 within the geologic formations underlying the earth and possible migration to the surface. This area also encompasses developments to mitigate leakage, should it occur. Soils MM&V involves tracking carbon uptake and storage in the first several feet of topsoil and tracking potential leakage pathways into the atmosphere from the underlying geologic formation. This area is especially challenging due to the difficulty in detecting small changes in concentration above the background emissions (~370 ppm) that already exist in the atmosphere. Aboveground MM&V is specific to terrestrial sequestration and involves quantification of the above-ground carbon stored in vegetation. The Sequestration Program is developing instrumentation, detailed computer models and protocols for each of these areas.

Risk management efforts are being developed to encompass the life of a CO_2 storage project as described below:

Pre-injection. A clear picture of the target formation prior to injection (i.e, a baseline) is developed using core samples, fluid samples, and seismic evaluations. Optimal strategies for CO_2 injection are identified, and the flow of injected CO_2 is modeled over long time frames. As a part of the pre-injection assessment, developers consider different CO_2 leakage scenarios. Categories of leakage events include: (1) cap rock or seal failure through capillary failure, faults, or fractures; (2) CO_2 bypass of the cap rock via spillage or migration outside of the target reservoir; and (3) wellbore failure. Particularly in depleting gas or oil formations where many wells have been drilled and abandoned, wellbore failure may represent the highest CO_2 leakage risk. Both the amount of CO_2 leakage and the path that it travels are assessed. In preferred storage formations, a significant portion of any CO_2 leakage becomes trapped in overlying formations. The viability of a system will be judged based on the results of this pre-injection evaluation and only projects that promise very low risk of leakage will be pursued.

Operation. Once CO_2 injection begins, the transport of CO_2 into the formation will be monitored closely using time-lapse seismic, fluid samples from observation wells, and other data. The monitoring results will be used to both detect any CO_2 leaks or unexpected flow patterns and also to ground truth the reservoir models and hone their predictive capability.

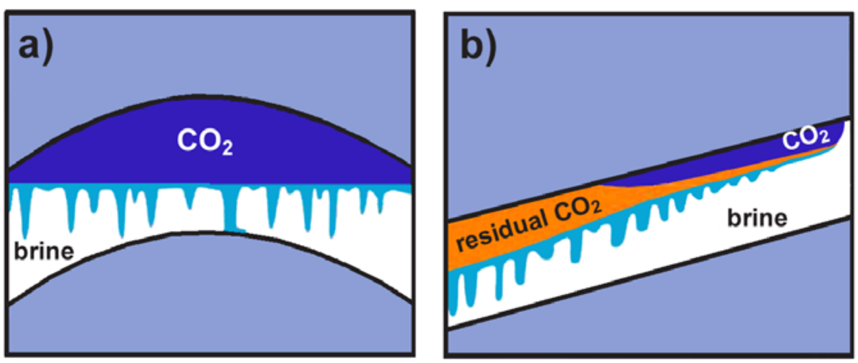
Closure. CO_2 monitoring will be continued after injection is completed until such a time as it is shown that the stored CO_2 is stable. This may be five to ten years after injection has ceased. A combination of reservoir modeling and CO_2 monitoring snapshots will enable verification of long-term CO_2 storage permanence.

Post-closure. Protocols for long-term monitoring are currently under development. Long term monitoring will likely include a complete set of characterization and monitoring data which will be invaluable to ensure permanent storage of the sequestered CO_2.

Trapping Mechanisms and Mitigation of Leakage

Scientists have studied the behavior of CO_2 in underground formations and are developing methods for proactively minimizing the risk of CO_2 leakage. This work centers on an improved understanding of the mechanisms for CO_2 storage. The following is a list of key mechanisms.

- ***Cap rock trapping.*** A layer of low-porosity rock serves as a barrier to upward migration of CO_2.
- ***Pore trapping.*** Through capillary and surface tension forces, droplets of CO_2 become affixed into a rock pore space.
- ***Dissolution in brine solution.*** CO_2 is soluble in brine. At 1,900 psi and 30,000 ppm total dissolved solids, one gallon of brine holds 0.4 lbs CO_2.
- ***Mineralization.*** Once in solution CO_2 will react, albeit at a slow rate, with dissolved minerals to form solid mineral carbonates.
- ***Adsorption.*** Unmineable coal seams offer a unique storage mechanism as CO_2 molecules are adsorbed onto the surface of the coal. Adsorbed CO_2 exists as a condensed liquid and is immobile as long as the formation pressure is maintained.



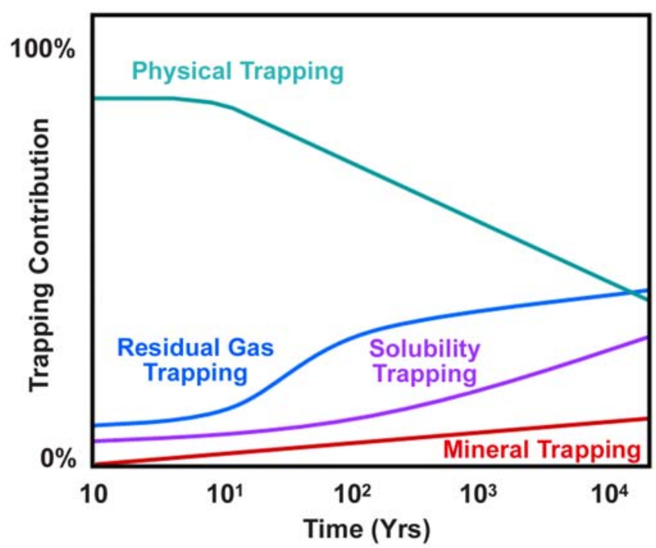
An understanding of CO_2 storage mechanisms will enable CO_2 injection field practices that enhance storage permanence. The figure above, taken from Stanford University, Global Climate Energy Project, June 2004, "Technical Report 2003-2004" http://gcep.stanford.edu/pdfs/technical_report_2004.pdf, is a schematic of CO_2 dissolution in two aquifers. The mobile CO_2 gas phase is dark blue, the dissolved aqueous CO_2 is light blue, residual CO_2 is orange, and the brine is not colored. a) CO_2 gas is held under a structural trap. Dissolution of CO_2 into the brine reduces the CO_2 gas phase volume. b) The CO_2 gas phase migrates along the top of a sloping aquifer, and leaves behind a region of residual CO_2 (i.e., CO2 trapped in pore space). In this case both dissolution and residual CO_2 saturation contribute to the decrease of the mobile CO_2 phase.

CO_2 that is trapped in pores, dissolved in brine, and mineralized will remain immobile and permanently sequestered. Research is aimed at developing injection techniques that maximize secure CO_2 storage via the trapping mechanisms described above. If CO_2 leakage occurs, steps can be taken to arrest the flow of CO_2 or mitigate negative effects. Examples include, lowering the pressure within the CO_2 storage formation to reduce the driving force for CO_2 flow and possibly reverse faulting or fracturing; increasing the pressure in the formation into which CO_2 is leaking, forming a pressure plug; intercepting the CO_2 leakage path; and plugging the region where leakage is occurring with low permeability materials. Additionally, research is underway to develop mitigation techniques that involved "controlled mineral carbonation" or "controlled formation of biofilms" that could be used to plug seepage/leakage points in a geologic formation.

Research is underway to develop mitigation techniques that could be used to plug seepage/leakage points in a geologic formation.

Important for consideration of long term CO_2 storage permanence is the understanding that CO_2 stored in a porous rock formation will tend to become more secure over time (100s of years) as these trapping mechanisms become more predominant, such as CO_2 becomes dissolved into brine or fixed into a mineral carbonate solid. Brine-containing dissolved CO_2 is slightly denser than brine without CO_2 and CO_2-saturated brine will migrate downward in a reservoir, displacing the lighter brine below it. This density effect causes a natural convection that brings the free CO_2 in contact with unsaturated brine. Directionally, mineralization will remove CO_2 from solution and drive further dissolution of CO_2, but the reactions are very slow and less understood.

In summary, the risks of long-term CO_2 storage in geologic formations can be addressed and managed as research provides improved rigorous pre-injection site characterization, close monitoring and accurate modeling of the fate and transport of injected CO_2, field practices to enhance the permanence of CO_2 storage, and capability to reliably detect and mitigate CO_2 leaks in the unlikely even that they occur.



Stable CO_2 stotage mechanisms dominate underground storage over long time frames, providing the promise of secure storage. Source; Sally Benson, 2004, plenary presentation GHGT-7

National Energy Technology Laboratory

626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236-0940
412-386-4687

3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880
304-285-4764

One West Third Street, Suite 1400
Tulsa, OK 74103-3519
918-699-2000

P.O. Box 750172
539 Duckering Bldg./UAF Campus
Fairbanks, AK 99775-0172
907-452-2559

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

R & D
facts

U.S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

Sequestration

06/2002

CARBON SEQUESTRATION SCIENCE

CONTACT POINTS

Dr. Curt M. White
Carbon Sequestration Science
Focus Area Leader
412-386-5808 phone
412-386-4806 fax
curt.white@netl.doe.gov

Diane (DeeDee) Newlon
Technology Transfer Manager
304-285-4086
r diane.newlon@netl.doe.gov

ADDRESS

National Energy
Technology Laboratory

626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236-0940
412-386-4604 fax

3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880
304-285-4469 fax

WEBSITE

www.netl.doe.gov/products/r&d/

Description

The goal of the Carbon Sequestration Science focus area is to identify and remove technical barriers and reduce costs associated with sequestration of carbon from energy processes. Effective carbon sequestration technologies and methods will provide long-range options for reducing CO_2 emissions from large stationary sources of CO_2. These reductions will ensure the continued availability of low-cost energy from the plentiful fossil energy resources within the United States.

Research at the Carbon Sequestration Science Laboratory will emphasize CO_2 separation and capture technologies, geological storage science, development of direct ocean storage approaches, and integrated process modeling, simulation and economic assessment. This research will stimulate innovation and develop novel concepts for carbon sequestration by partnering with universities, Federal laboratories, and private industry. Activities will span the broad carbon sequestration interest area and will focus on improving scientific understanding of the separation and capture of CO_2, the disposal of CO_2 in the deep oceans, and geologic sequestration.

As a part of this national research activity, the focus area for Carbon Sequestration Science will conduct research ranging from fundamental studies to small-scale proof-of-concept research on selected processing options. Systems analysis via computer modeling and simulation of approaches to carbon sequestration will be developed in-house for use in evaluating the various approaches.

The purpose of the Carbon Sequestration focus area at the NETL is to serve as the focal point for all carbon sequestration R&D activities performed with in-house resources sponsored primarily by the Office of Fossil Energy. Its specific role is to:

- Identify research directions and construct a balanced portfolio of activities integrated with the national sequestration R&D program,
- Conduct portions of the R&D portfolio with in-house resources,
- Serve as a hub for the conduct of systems analysis on sequestration technology options.

Carbon Sequestration Science

Benefits

- Generate ideas and build expertise
- Refine program focus as promising approaches emerge
- Provide scientific basis to define and develop pilot-scale activities
- Strengthen existing partnerships
- Facilitate regional NETL/University/Industry partnerships
- Increase participation in key international activities

Goal

Our goal is to have the Carbon Sequestration Science focus area, including its partners, recognized as the premier research laboratory in the area of carbon sequestration. This will be accomplished by:

- Providing scientific insights that lead to technological options for long-term stabilization of CO_2 and other GHG's,
  - provide scientific basis for sequestration to allow continued use of fossil energy resources,
  - develop scientific understanding of processes for separation, capture, reuse, and storage of CO_2 and other GHG's, and,
  - address geological, chemical, and biological sequestration barrier issues.
- Ensuring full attention to potential consequences of sequestration options,
- Providing scientific information and systems analysis from a non-conflicted perspective.

A continuing investment in this focus area will result in the identification of CO_2 capture technologies and sequestration methods that are technically feasible, environmentally acceptable, and economically well defined. Should national decisions be made regarding the need to sequester CO_2, then the capture and sequestration techniques developed as a result of this R&D activity can be deployed commercially in the U.S. and abroad.

Milestones

- In FY2001, the low and high-pressure water tunnel laboratories will be completed. Determine the fate of CO_2 in the ocean water column; evaluate microbes in coal seams; develop simulation models of CO_2 displacement of coal-bed methane; evaluate the effect of ground water pH on coal seam sequestration capacity; and study formation of metal carbonates during reaction of CO_2 with minerals high Ca and Mg.
- In FY2002, the Capture and Geologic Storage laboratories will be completed. Determine the influence of minor flue gas constituents on hydrate formation; study the effects of coal variability (e.g., rank) on sequestration capacity; optimize parameters for CO_2 or multipollutant wet scrubbing; and evaluate the potential for using high volume waste materials (e.g., FGD sludge and fly ash) in sequestration.
- In FY2003, capture and storage research activities will be initiated and work to install the Integrated Carbon Sequestration Test Facility is initiated. Complete the coal seam simulation model (including trace gas components); investigate acid mine drainage (AMD) waters (high in metals content) as a sink for CO_2; evaluate the use of standard pipelines to transport flue gas to sequestration sites; evaluate the effect of trace amounts of SO_2 and NOx on corrosion of CO_2 pipelines and identification of initial capture technologies for joint scale-up Federal/ partnership evaluation.
- In FY2004, assembly of the Integrated Carbon Sequestration Test Facility continues. A novel dry-scrubbing process is investigated for CO_2 removal from simulated Vision 21 gas streams; verify simulation model with experimental results; and improve the kinetics of CO_2-mineral sequestration reactions.
- In FY2005, testing of promising process concepts will be initiated in the Integrated Carbon Sequestration Research Facility. Develop universal flow equations for injection of CO_2 into geologic formations; and evaluate biological and microbiological effects of CO_2 disposal in ocean.

R & D facts
U.S. Department of Energy
National Energy Technology Laboratory

06/2002

Sorbent and Catalyst Preparation Facilities

CONTACT POINTS

Ranjani Siriwardane
Senior Scientist
304-285-4513
ranjani.siriwardane@netl.doe.gov

Diane (DeeDee) Newlon
Technology Transfer Manager
304-285-4086
r diane.newlon@netl.doe.gov

ADDRESS

National Energy Technology Laboratory

3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880
304-285-4469 fax

626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236-0940
412-386-4604 fax

WEBSITE

www.netl.doe.gov/products/r&d/

Capabilities

The National Energy Technology Laboratory (NETL) has facilities for the small scale preparation of sorbents/catalysts suitable for fixed, moving and fluid bed reactor applications. Equipment is also available for ASTM attrition tests, crush measurements and particle size analysis.

Mixer Pelletizer

- Mixing of different solid powders
- Agglomeration of solid materials for the preparation of pellets with 1-6 mm diameter, suitable for fixed bed reactor tests.
- 5 lbs batch production

Rotary Vacuum Evaporator

- Wet impregnation of porous substrates
- Batch production up to 2 lbs
- Particle size up to 1 cm in diameter

Lab-Scale Spray Dryer

- Semi-continuous production up to 1 lbs
- Particle sizes range from 40 to 100 microns in diameter
- Suitable for transport/fluid bed reactor applications

Dome Extruder

- Continuous production up to 15 lbs
- Particle sizes range from 0.5 mm to 5 mm in diameter
- Extrudates suitable for fixed bed reactor applications

Particle Spheronizer/Marumerizer

- Semi-continuous production up to 15 lbs
- Particle sizes range from 0.5 mm to 6 mm in diameter
- Transforms pellets into spherical shape

NETL

Sorbent and Catalyst Preparation Facilities

Attrition Tester for Materials Suitable for Fluid Bed/ Transport Reactor Applications

- Standard Test Method for Determination of Attrition and Abrasion of Powdered Catalysts by Air Jets - ASTM D 5757-95
- Suitable for particles with sizes less than 500 microns

Attrition Tester for Materials Suitable for Moving/ Fixed Bed Reactor Applications

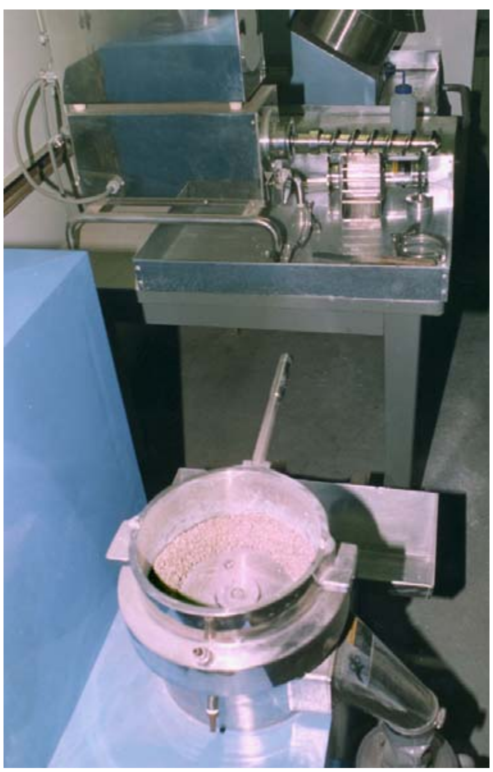
- Standard Test Method for Attrition and Abrasion of Catalysts and Catalyst Carriers - ASTM D 4058-92
- Suitable for particle sizes greater than 1 mm

Crush Strength Measurements

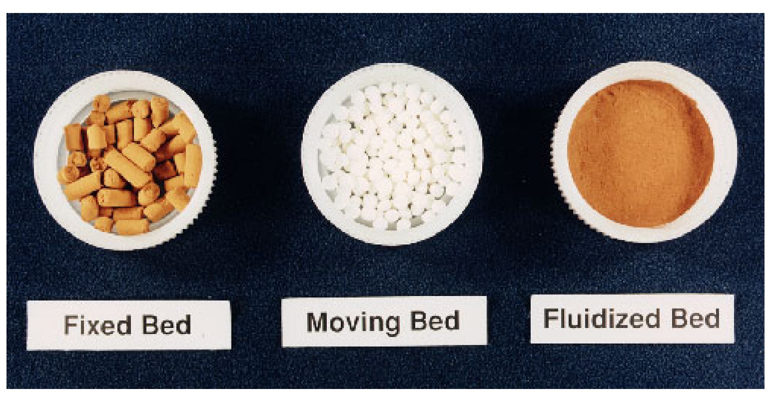
- Measurement of force necessary to break pellets using a push-pull gauge
- Suitable for mechanical strength measurements for materials used in fixed/moving bed reactor applications

Particle Size Analysis

- ASTM sieves for particles larger than 300 microns
- Coulter counter for water insoluble particles smaller than 300 microns
- API aerosizer for water soluble particles smaller than 300 microns



Sorbent/Catalyst Preparation Facilities



Sorbents

R & D facts
U.S. Department of Energy
National Energy Technology Laboratory

06/2002

Advanced Analytical Instrumentation and Facilities for In Situ Reaction Studies

CONTACT POINTS

Ranjani Siriwardane
Senior Scientist
304-285-4513
ranjani.siriwardane@netl.doe.gov

Diane (DeeDee) Newlon
Technology Transfer Manager
304-285-4086
r diane.newlon@netl.doe.gov

ADDRESS

National Energy Technology Laboratory

3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880
304-285-4469 fax

626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236-0940
412-386-4604 fax

WEBSITE

www.netl.doe.gov/products/r&d/

Capabilities

Various types of analytical instrumentation to conduct standard chemical/physical characterizations and to study in-situ gas-solid reactions are available at the National Energy Technology Laboratory. These systems have unique capabilities to study in-situ gas/solid reactions at high temperature and/or high pressure. The systems can be utilized to determine reaction mechanisms, the extent of reactions and reaction kinetics. Analytical instrumentation includes both surface and bulk analysis techniques.

Thermogravimetric Analysis (TGA) Systems

- Determination of both the extent of gas/solid reactions and chemical kinetics
- High temperature and high pressure capabilities

Fourier Transform Infrared Spectroscopy (FTIR) with High Temperature Diffuse Reflectance Accessory/Gas Exposure Cell

- Capability to study reaction mechanisms by identifying intermediates and reaction products formed in-situ during gas/solid reactions.
- Chemical characterization and structural changes of materials.

Scanning Electron Microscopy/X-Ray Microanalysis

- Determination of elemental composition and distribution
- Determination of surface morphology of materials at various magnifications through secondary electron and backscatter electron image acquisition
- Image processing and analysis
- Insitu analysis at high temperature
- Gas exposure capabilities to study gas/solid reactions
- Multi-sample analysis capabilities

X-Ray Photoelectron and Auger Electron Spectroscopy

- Determination of surface elemental composition and oxidation states of solid materials
- Insitu analysis at high temperatures
- Gas exposure capabilities to study gas/solid reactions
- Multi-sample analysis capabilities

Atomic Force Microscope

- Analysis at both room temperature and high temperature
- Gas exposure capabilities

Advanced Analytical Instrumentation and Facilities for In Situ Reaction Studies

Other Analytical Capabilities for Physical and Chemical Characterization

Physical Characterization

- Particle Size Analyzer
- BET Surface Area & Pore Volume Analyzer
- Helium Density Analyzer
- Viscometers
- Specific Gravity Meter
- LECO Calorimeter

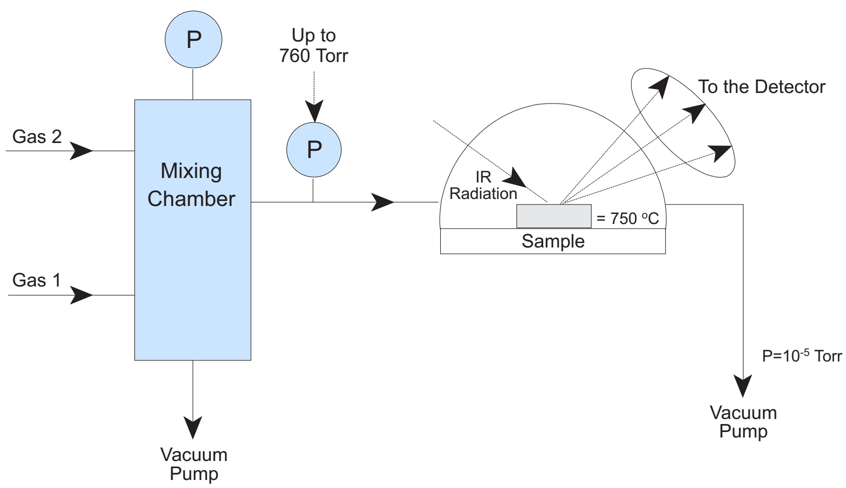
Reaction Studies

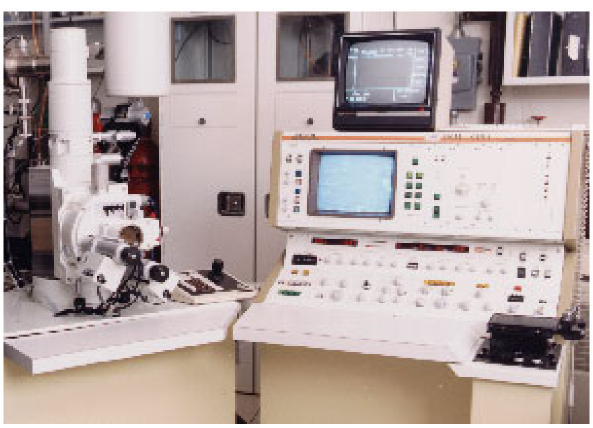
- Volumetric Absorption Apparatus
- Micro Reactor

Chemical Analysis

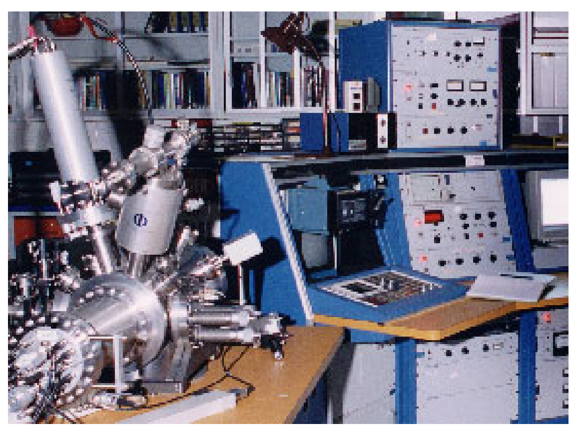
- X-ray Florescence
- Atomic Absorption Spectroscopy
- C, H, N Analyzer
- LECO Sulfur Analyzer
- Moisture, Ash & Volatile Matter Analyzer
- Gas Chromatography
- Nuclear Magnetic Resonance
- Mass Spectroscopy
- Inductively Coupled Plasma Spectroscopy

Diffuse Reflectance FTIR





Scanning Electron Microscopy



X-Ray Photo Electron and Auger Electron Spectroscopy

R & D facts

U.S. Department of Energy
National Energy Technology Laboratory

Sequestration

06/2002

Small-scale Facilities for Air Pollution Research

Contact Points

Henry Pennline
Chemical Engineer
412-386-6013
henry.pennline@netl.doe.gov

Diane (DeeDee) Newlon
Technology Transfer Manager
304-285-4086
r diane.newlon@netl.doe.gov

Address

National Energy Technology Laboratory

626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236-0940
412-386-4604 fax

3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880
304-285-4469 fax

Website

www.netl.doe.gov/products/r&d/

Capabilities

NETL is conducting research on the cleanup of flue gas produced by combustion of fossil fuels. This effort directly supports the goal of the Advanced Research and Environmental Technology Program to ensure continuing utilization of coal in an environmentally and economically acceptable manner. Novel technologies are being developed that can abate the air pollutants found in flue gas, such as sulfur dioxide (SO_2), nitrogen oxides (NO_X), hazardous air pollutants (also referred to as air toxics) and fine particulates, and carbon dioxide (CO_2).

Research at NETL has focused on: (1) investigating air toxics produced by burning various coals, with a particular emphasis on the speciation of mercury and the control of the various mercury species; (2) dry, regenerable sorbent processes that use a metal-oxide sorbent to simultaneously remove SO_2 and NO_X; (3) catalysts for selective catalytic reduction (SCR)-type NO_X control; and (4) the capture of CO_2 removed from flue gas produced by fossil fuel combustion.

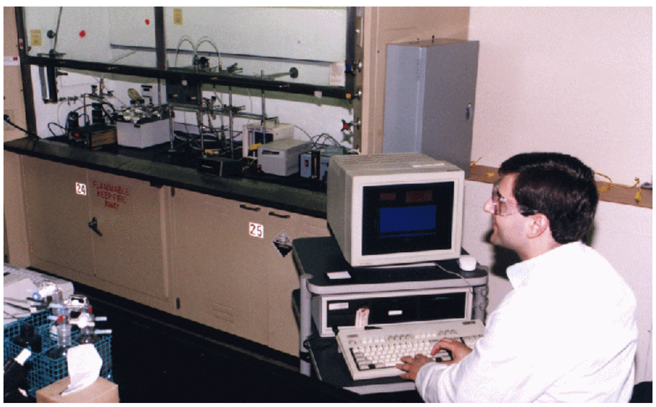
Examples of results that can be obtained in NETL's various small-scale reactor facilities include:

- Using a thermogravimetric analyzer and a microbalance to investigate adsorption or regeneration kinetics of dry, regenerable sorbents used to remove CO_2, SO_2, and NO_X from simulated flue gas. The large flow of gas over the small charge of sorbent (~ 50 mg) approximates a differential reactor, facilitating the interpretation of the kinetics by changes in weight.
- Using packed-bed reactors to screen sorbents or sorbent/catalysts for their reactivity toward the removal of certain gaseous pollutants. Continuous emissions monitors that can analyze for the various gas constituents at the reactor exit follow the behavior of the substance of interest.
- Coupling continuous analysis (atomic fluorescence spectrophotometer) of a difficult-to-measure gaseous pollutant (mercury) with a reactor scheme to screen novel sorbents for the removal of mercury from flue gas.
- Using unique schemes to investigate CO_2 capture: a bench-scale, packed-column scrubbing apparatus to study improved efficiency for wet chemical scrubbing of CO_2 from flue gas.

Small-scale Facilities for Air Pollution Research

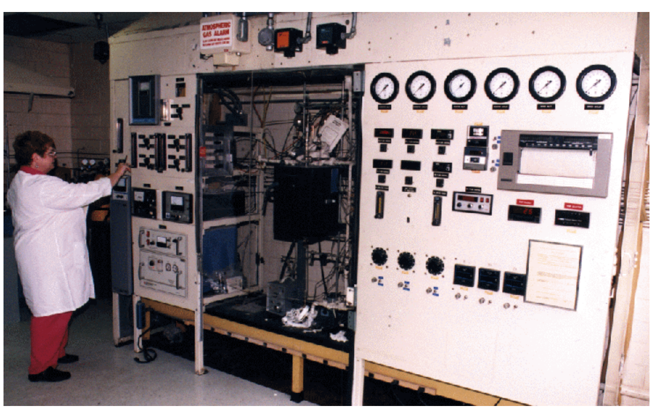
Opportunities

- Develop kinetic expressions for various gas-solid reactions.
- Screen various sorbents for removal of specific pollutants from flue gas.
- Characterize catalytic and non-catalytic gas-solid reaction systems by establishing experimental databases.
- Evaluate dry and wet scrubbing techniques for the capture of greenhouse gases.
- Work with industry using the various NETL facilities.

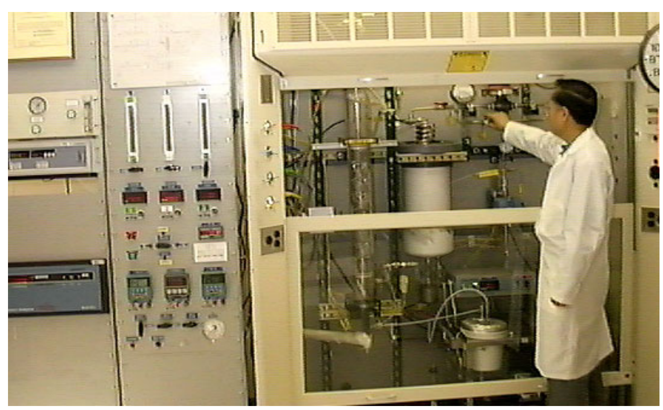


Data Acquisition System
Linked to Mercury Analyzer

Solid Sample Being Loaded Into
Thermogravimetric Analyzer



Packed-Bed Reactor Setup

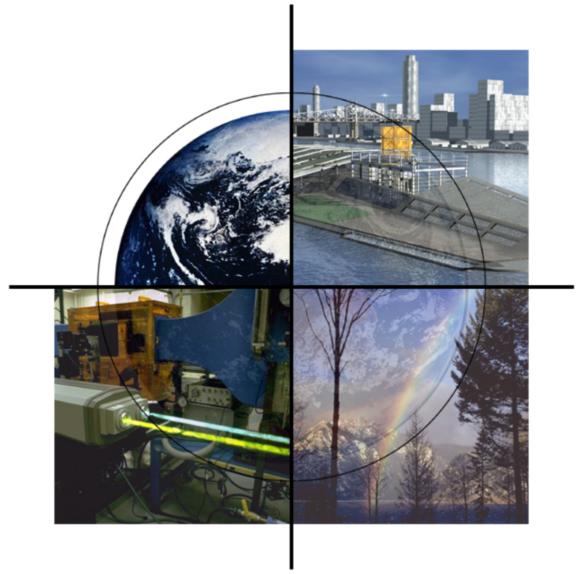


Packed-Column Scrubbing Apparatus

Regional Partnerships

Page left blank to accommodate 2-sided printing

Regional Carbon Sequestration Partnerships

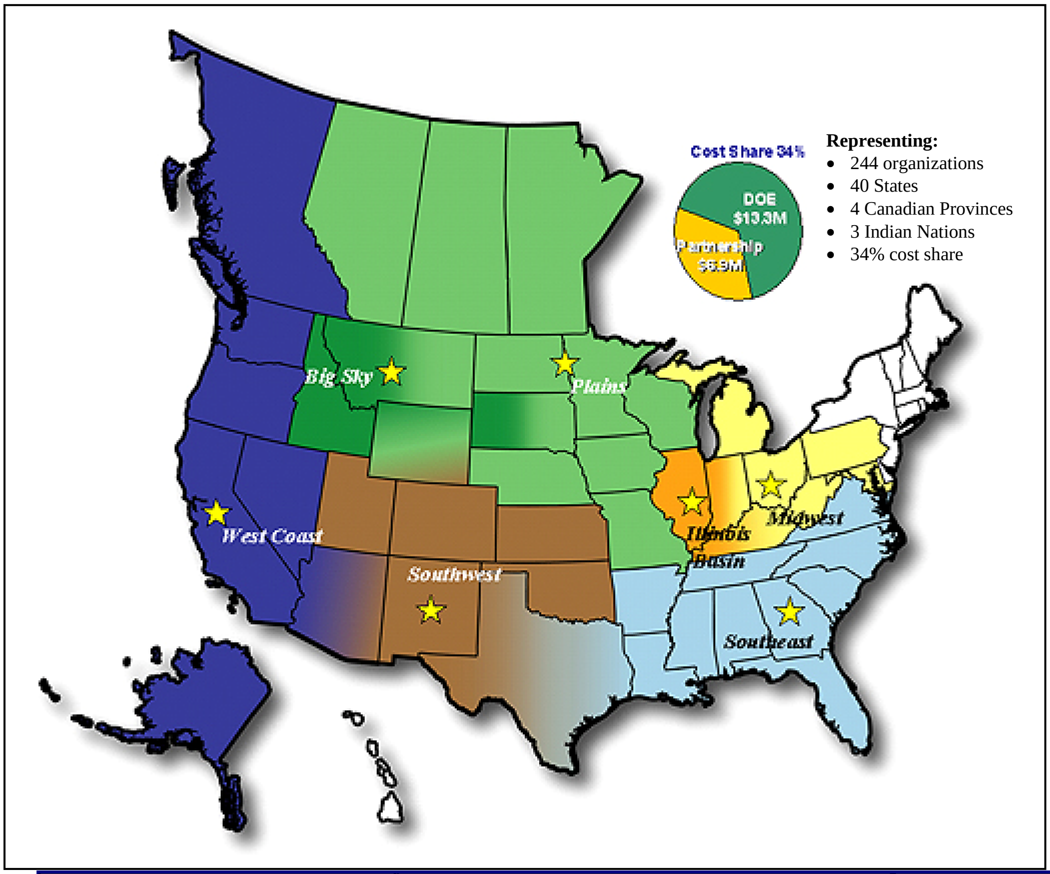


The U.S. Department of Energy has seven partnerships of state agencies, universities, and private companies that will form the core of a nationwide network to help determine the best approaches for capturing and permanently storing gases that can contribute to global climate change. The partnerships include 244 organizations spanning 40 states, three Indian nations, and four Canadian provinces. In announcing the initiative in November of 2003, former Secretary of Energy Spencer Abraham said the partnerships would become "the centerpiece" of expanded federal efforts to investigate the potential for carbon sequestration. The partnerships are a key part of President Bush's Global Climate Change Initiative (GCCI).

Regional Carbon Sequestration Partnerships are a government/industry effort to create a nationwide network of partnerships to determine the most suitable technologies, regulations, and infrastructure needs for carbon capture, storage and sequestration in different areas of the country.

This initiative directly supports the President's Global Climate Change Initiative (GCCI) goal of reducing greenhouse gas intensity by 18% by 2012 and will help ensure that a suite of commercially-ready sequestration technologies are available for the 2012 technology assessment mandated by the GCCI. The geographical differences in fossil fuel use and sequestration sinks across the United States dictates that regional approaches will be required to address the sequestration of CO_2.

Regional Partnerships



Partnership	Partnership Lead	States Represented
Midwest Regional Carbon Sequestration Partnership	Battelle Memorial Institute	IN, KY, MI, MD, OH, PA, WV
An Assessment of Geological Carbon Sequestration Options in the **Illinois Basin**	The Board of Trustees of the University of Illinois, Illinois State Geological Survey	IL, IN, KY
Southeast Regional Carbon Sequestration Partnership	Southern States Energy Board	AL, AR, FL, GA, LA, MS, NC, SC, TN, TX, VA
Southwest Regional Partnership for Carbon Sequestration	New Mexico Institute of Mining and Technology	AZ, CO, KS, NE, NM, OK, TX, UT, WY
West Coast Regional Carbon Sequestration Partnership	State of California, California Energy Commission	AK, AZ, CA, NV, OR, WA
Big Sky Regional Carbon Sequestration Partnership	Montana State University	ID, MT, SD, WY
Plains CO_2 Reduction Partnership	University North Dakota - Energy & Environmental Research Center	IA, MO, MN, ND, NE, MT, SD, WI, WY

Project Title	Primary Contractor	Fact Sheet Listing
Midwest Regional Carbon Sequestration Partnership	Battelle Memorial Institute	R-4
An Assessment of Geological Carbon Sequestration Options in the Illinois Basin	The Board of Trustees of the University of Illinois, Illinois State Geological Survey	R-6
Southeast Regional Carbon Sequestration Partnership	Southern States Energy Board	R-8
Southwest Regional Partnership for Carbon Sequestration	New Mexico Institute of Mining and Technology	R-10
West Coast Regional Carbon Sequestration Partnership	State of California, California Energy Commission	R-12
Big Sky and Great Plains Regional Carbon Sequestration Partnership	Montana State University	R-14
Plains CO_2 Reduction Partnership	University North Dakota - Energy & Environmental Research Center	R-18

* Factsheet Under Development

Page left blank to accommodate 2-sided printing

PROJECT facts

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

4/2004

MIDWEST REGIONAL CARBON SEQUESTRATION PARTNERSHIP (MRCSP)

Background

The U.S. Department of Energy has designated seven partnerships of state agencies, universities, and private companies that will form the core of a nationwide network that will help determine the best approaches for capturing and permanently storing gases that can contribute to global climate change. All together, the partnerships include more than 140 organizations, spanning 33 states, three Indian nations, and two Canadian provinces.

The seven partnerships will develop the framework needed to validate and potentially deploy carbon sequestration technologies. They will evaluate and determine which of the numerous sequestration approaches that have emerged in the last few years are best suited for their specific regions of the country. They will also begin studying possible regulations and infrastructure requirements that would be needed should climate science indicate that sequestration be deployed on a wide scale in the future.

Description

Battelle Memorial Institute is leading one of those partnerships. Battelle has built a unique public-private partnership, the Midwest Regional Carbon Sequestration Partnership (MRCSP), to tackle the challenge of reducing CO_2 emissions while simultaneously protecting the industrial infrastructure of the Midwest Region. The partnership will assess the technical, economic, and social acceptability of carbon sequestration as part of a strategy to reduce CO_2 emissions in the United States. The MRCSP will focus its research in the U.S. industrial heartland: Indiana, Ohio, Kentucky, West Virginia, Pennsylvania, Michigan and Maryland. This Region is a concentrated center for industrial and manufacturing activities which it maintains because of the affordable energy made possible by abundant domestic energy resources and a quality workforce. MRCSP will identify greenhouse gas sources in the region and assess the ability and cost of capturing and sequestering these emissions in the region's numerous deep geologic formations and abundant agricultural, forest, and degraded land systems. In addition, MRCSP will engage the public and elected officials at all levels to communicate the issues and the potential value associated with terrestrial and geologic sequestration. MRCSP will also examine existing regulatory and other barriers that might hinder our ability to cost effectively deploy these technologies and will define strategies for overcoming these barriers.

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Charles Byrer
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-4547
charles.byrer@netl.doe.gov

Ronald A. Cudnik
Vice President for the Energy Products Division
Battelle
505 King Avenue
Columbus, OH 43201
614-424-7316
cudnikr@battelle.org

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

Midwest Regional Carbon Sequestration Partnership (MRCSP)

Primary Project Goal

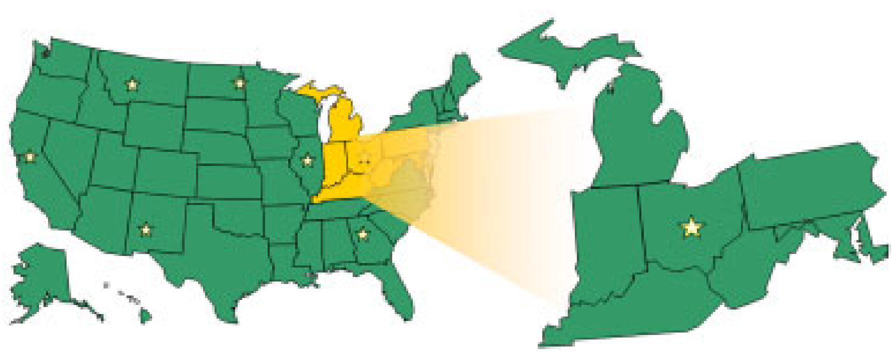
To identify green house gas sources in the partnership's region and determine the technical feasibility and cost of capturing and sequestering these emissions in deep geologic formations and in forests and agriculturally degraded land systems

Objectives

- To identify greenhouse gas sources in the region and assess the ability and cost of capturing and sequestering these emissions in the region's numerous deep geologic formations and abundant agricultural, forest, and degraded land systems.
- To engage the public and elected officials at all levels and dialog on the issues and potential values associated with terrestrial and geologic sequestration.
- To examine existing regulatory and other barriers that might hinder the ability to cost-effectively deploy these technologies and to define strategies for overcoming these barriers.
- To translate this accumulated knowledge into practical implementation approaches. At the end of two years, the partnerships will have developed action plans for public outreach and education, regulatory compliance, and technology validation to support potential small scale tests within the region.

Benefits

Battelle researchers are currently leading the U.S. Department of Energy's Mountaineer Project, which is evaluating the feasibility of sequestering in deep saline formations CO_2 from one of American Electric Power's modern coal-fired units. Never before has a team of researchers with skills of such depth and breadth worked together to advance key energy and climate management technologies, such as CO_2 sequestration. This project will determine whether there is a cost-effective way to reduce CO_2 emissions in the high-emissions Illinois Basin region.



Midwest Regional Carbon Sequestration Partnership - (Region 1)

PROJECT PARTNERS

Battelle Memorial Institute

British Petroleum

Nordic

Arch Coal Inc.

American Electric Power

Cinergy

CONSOL Energy Inc.

First Energy

Wisconsin Energy Corporation

Indiana Geological Survey

Kentucky Geological Survey

Ohio Coal Development Office

Ohio Division of Geological Survey

Ohio Environmental Office

Pennsylvania Geological Survey

West Virginia Geological and Economic Survey

Ohio State University

Pennsylvania State University

Purdue University

West Virginia University

National Regulatory Research Institute

The Keystone Center

Michigan State University

University of Maryland

Western Michigan University

Maryland Geological Survey

AES Warrior Run, Inc.

Maryland Energy Administration

DTE Energy

Alliance Resources Partners

Constellation Energy

COST

Total Project Value: $3,513,513

DOE: $2,410,967

Non-DOE Share: $1,102,546

Proj243.pmd

PROJECT
facts

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

Southeast Regional Carbon Sequestration Partnership (SERCSP)

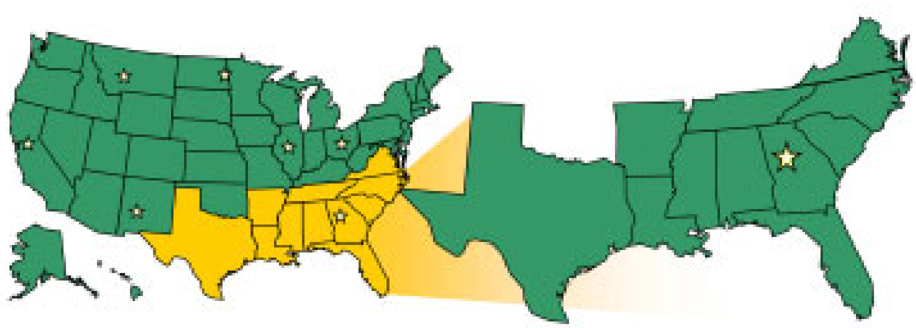
Background

The U.S. Department of Energy has selected the seven partnerships of state agencies, universities, and private companies that will form the core of a nationwide network that will help determine the best approaches for capturing and permanently storing gases that can contribute to global climate change. All together, the partnerships include more than 140 organizations, spanning 33 states, three Indian nations, and two Canadian provinces.

The seven partnerships will develop the framework needed to validate and potentially deploy carbon sequestration technologies. They will evaluate and determine which of the numerous sequestration approaches that have emerged in the last few years are best suited for their specific regions of the country. They will also begin studying possible regulations and infrastructure requirements that would be needed should climate science indicate that sequestration be deployed on a wide scale in the future.

Description

The Southeast Regional Carbon Sequestration Partnership SERCSP, led by the Southern States Energy Board (SSEB), Norcross, GA, represents the eleven southeastern states (Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Texas and Virginia). SERCSP will accomplish its objectives by defining similarities in the nine state region; characterizing the region relative to sources, sinks, transport, sequestration options, and existing and future infrastructure requirements; identifying and addressing issues for technology deployment; developing public involvement and education mechanisms; identifying the most promising capture, sequestration, and transport options; and developing action plans for implementation and technology validation.



Southeast Regional Carbon Sequestration Partnership

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Karen Cohen
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-6667
karen.cohen@netl.doe.gov

Ken Nemeth
Executive Director
Southern States Energy Board
6325 Amherst Court
Norcross, GA 30092
770-242-7712
nemeth@sseb.org

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

Southern States Energy Board (SSEB)

Electric Power Research Institute (EPRI)

Mississippi State University (MSU) Diagnostic Instrumentation Analysis Laboratory (DIAL)

Massachusetts Institute of Technology (MIT)

Tennessee Valley Authority (TVA) Public Power Institute (PPI)

Winrock International

Augusta Systems Inc.

Applied Geo Technologies (AGT)

Geologic Survey of Alabama (GSA)

Susan Rice and Associates

Advanced Resources International

The Phillips Group

RMS Research

COST

Total Cost:
$ 1,999,885

DOE/Non-DOE Share:
$1,599,908 / $ 399,977

Duration of Contract:
24 Months

SERCSP will define the geographic boundary of the study. CO_2 sources, sinks, and transport requirements will be described and entered into a GIS system. An assessment of public involvement and educational needs will be conducted, and an outreach plan will be developed so that stakeholders can help identify and implement regional CO_2 sequestration measures. Safety, regulatory, and permitting requirements within the region will be assessed in consultation with regulatory agencies, state public utility commissions, and oil and gas commissions. Assessment of ecosystem impacts will be completed, and an action plan to address impact issues will be developed. Monitoring and verification requirements will be established, along with protocols for geologic and terrestrial sequestration, and measurement of stack emissions of CO_2.

Primary Project Goal

The primary project goal is to promote the development of the framework and infrastructure necessary for the validation and deployment of carbon sequestration technologies, and to evaluate options and potential opportunities for regional CO_2 sequestration.

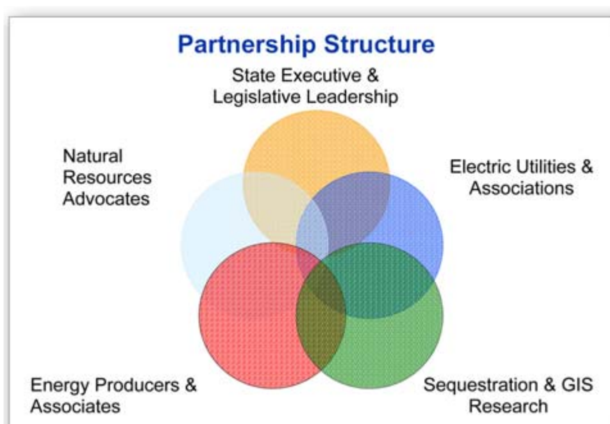
Objectives

- Define similarities among the nine states in the region.
- Characterize the region relative to sources, sinks, transport, sequestration options, and existing and future infrastructure requirements.
- Identify and address issues involved with technology deployment.
- Develop public involvement and education mechanisms.
- Identify the most promising capture, sequestration, and transport options.
- Develop action plans for implementation and technology validation.

Benefits

SECSRP's study for this nine state region will result in the following specific programmatic benefits:

- Support the United States Department of Energy's (DOE) Carbon Sequestration Program by promoting the development of the framework and infrastructure necessary for the validation and deployment of carbon sequestration technologies.
- Support the President's Global Climate Change Initiative goal of reducing greenhouse gas intensity by 18 percent by 2012.
- Evaluate options and potential opportunities for regional CO_2 sequestration.



Proj278.pmd

PROJECT facts

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

02/2004

Southwest Regional Partnership for Carbon Sequestration

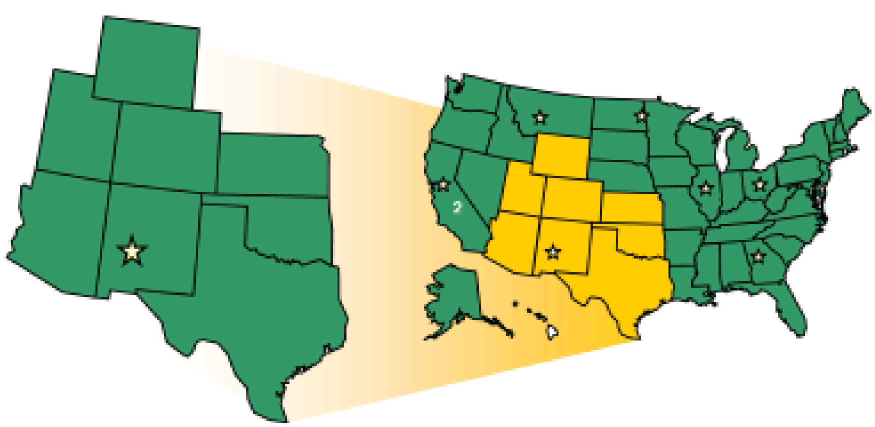
Background

The U.S. Department of Energy has selected the seven partnerships of state agencies, universities, and private companies that will form the core of a nationwide network that will help determine the best approaches for capturing and permanently storing gases that can contribute to global climate change. All together, the partnerships include more than 140 organizations, spanning 33 states, three Indian nations, and two Canadian provinces.

The seven partnerships will develop the framework needed to validate and potentially deploy carbon sequestration technologies. They will evaluate and determine which of the numerous sequestration approaches that have emerged in the last few years are best suited for their specific regions of the country. They will also begin studying possible regulations and infrastructure requirements that would be needed should climate science indicate that sequestration be deployed on a wide scale in the future.

Description

The Southwest Regional Partnership for Carbon Sequestration (SRPCS), led by the New Mexico Institute of Mining and Technology, Socorro, NM, will disseminate existing regulatory/permitting requirements, assess the most appropriate sequestration strategies, and evaluate and rank sequestration technologies for CO_2 capture and storage in the Southwest region, which includes Arizona, Colorado, New Mexico, Oklahoma, and Utah. In the Southwest Region, over 95% of CO_2 emissions result from fossil fuel combustion, and about half of these emissions are from power plants. Geologic storage options include coal beds, natural gas and



Midwest Regional Carbon Sequestration Partnership - (Region 4)

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

David Hyman
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-6572
david.hyman@netl.doe.gov

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

BUSINESS CONTACT

Alan A Reisinger
505-835-5948
505-835-6031 fax
alan@prrc.nmt.edu

TECHNICAL CONTACT

Brian McPherson
505-835-5834
505-835-6031 fax
brian@nmt.edu

BUSINESS OFFICE ADDRESS

New Mexico Institute of Mining and Technology
Petroleum Recovery Research Center
801 Leroy Place
Socorro, NM 87801-4796

COST

Length of Contract:
24 Months

Total Project Value:
$2,145,506

DOE/Non-DOE Share:
$1,600,000/ $545,506

CO_2 fields, depleted and marginal oil fields, and deep saline aquifers. One option the partnership will explore is the viability of supplanting the CO_2 currently produced from natural CO_2 reservoirs, used for enhanced oil and natural gas recovery, with anthropogenic power plant CO_2. The presence of CO_2 pipelines may improve the viability of this possibility. Although terrestrial CO_2 sequestration appears to be a viable alternative in several parts of the Southwest Region, low rainfall in some areas may decrease the value of this option.

A website network will be set up to share information, store data, and help with decision-making and future management of carbon sequestration in the region. Over twenty partners, including the Navajo nation, state geologic surveys, coal, oil and natural gas companies, utilities, technology companies, and universities, make up this partnership.

Primary Project Goal

The goal of this project is to develop a sequestration strategy for the region, subject to the constraints unique to the Southwest, such as water resource availability. The assessment will not only identify the available technologies on which the strategy relies, but will also determine technological gaps.

Objectives

- To prepare a comprehensive assessment of the CO_2 sequestration aspects of the region, including sources, sinks, transport, sequestration options, and existing and future infrastructure requirements.
- To identify and address sequestration implementation issues.
- To initiate public outreach and assess public acceptance of CO_2 sequestration.
- To identify and rank sequestration options for the Southwest region.

Benefits

This project will benefit the U.S. by providing a comprehensive assessment of the sources and potential sinks for CO_2 in the Southwest region. This data can be integrated with the data from other partnerships to provide a data base covering the entire nation. This effort will also provide information to evaluate potential pilot sequestration projects in the Southwest.

PARTNERS

New Mexico Institute of Mining and Technology

Western Governors Association

Advanced Resources International

Bureau of Economic Geology
University of Texas at Austin

Burlington Resources
Center for Energy and Economic Development

ChevronTexaco ERTC

ChevronTexaco Permian Business Unit

ConocoPhillips

Intermountain Power Agency

Interstate Oil and Gas Compact Commission

Kansas Geological Survey

Kinder Morgan CO_2

Marathon Oil Company

McNeill Technologies

Navajo Nation

Nevada Bureau of Mines & Geology

Oklahoma Gas and Electric

Oxy Permian Ltd.

PacifiCorp

Public Service Co. of New Mexico

Tucson Electric Power Company

WERC

Wyoming State Geological Survey

Yates Petroleum Corporation

PROJECT facts

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

Sequestration

02/2004

WEST COAST REGIONAL CARBON SEQUESTRATION PARTNERSHIP

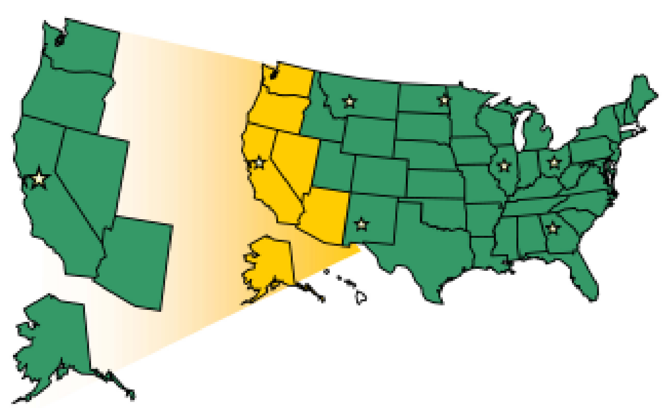
Background

The U.S. Department of Energy has selected the seven partnerships of state agencies, universities, and private companies that will form the core of a nationwide network that will help determine the best approaches for capturing and permanently storing gases that can contribute to global climate change. All together, the partnerships include more than 140 organizations, spanning 33 states, three Indian nations, and two Canadian provinces.

The seven partnerships will develop the framework needed to validate and potentially deploy carbon sequestration technologies. They will evaluate and determine which of the numerous sequestration approaches that have emerged in the last few years are best suited for their specific regions of the country. They will also begin studying possible regulations and infrastructure requirements that would be needed should climate science indicate that sequestration be deployed on a wide scale in the future.

Description

The West Coast Regional Carbon Sequestration Partnership (WCRCSP), led by the California Energy Commission, Sacramento, CA, plans to identify, characterize, and locate CO_2 emission sources in the region and determine capture and long-term sequestration methods by enlisting the help of numerous federal, state, and local government agencies and industry sources. WCRCSP is comprised of representatives from universities, national labs, nonprofit organizations, technology vendors, oil and gas companies, and policy oriented organizations from Alaska, Arizona, California, Nevada, Oregon, and Washington.



West Coast Regional Carbon Sequestration Partnership - (Region 5)

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

David Hyman
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-6572
david.hyman@netl.doe.gov

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

BUSINESS CONTACT

Lisa A Johnson
916-654-4276
916-654-4076 fax
ljohnson@energy.state.ca.us

TECHNICAL CONTACT

Terry Surles
916-654-4878
916-654-4676 fax
tsurles@energy.state.ca.us

BUSINESS OFFICE ADDRESS

1516 9th Street, MS 1
Sacramento, CA 95814-5512

COST

Length of Contract:
24 Months

Total Project Value:
$2,145,506

DOE/Non-DOE Share:
$1,600,000 / $545,506

The West Coast Region accounts for more than 11% of the nation's CO_2 emissions, with the bulk of these being from California. Total CO_2 emissions from the industrial and utility sectors, which have point sources that are most amenable to capture, are about 56 million tons of carbon equivalent per year. The region offers significant potential for sequestration in porous sediments, especially the brine formations of the Central Valley. Of particular interest is the use of CO_2 for enhanced oil recovery. The West Coast Region has a wealth of forest and agricultural lands, where improved management practices could also sequester substantial quantities of carbon. Technology discussions, regional meetings and joint research will be used to maintain an open dialogue with stakeholders so that a regional strategy for terrestrial and geologic carbon sequestration projects that meet the area's near- and long-term needs can be developed. Demonstration projects will be identified, and plans for their effective implementation will be developed.

Primary Project Goal

The overall goal of this project is to identify the most cost effective, technically feasible, and publicly acceptable options for terrestrial and geologic carbon sequestration in the region.

Objectives

- To develop a geographic information system (GIS) database for characterizing the sources, the potential sinks, and the transportation infrastructure for CO_2 in the region.
- To evaluate region-specific issues affecting technology deployment.
- To implement local and regional public outreach programs.
- To identify optimal demonstration opportunities for geologic and terrestrial sequestration in the region.

Benefits

This project will benefit the U.S. by providing a comprehensive assessment of the sources and potential sinks for CO_2 in the West Coast Region. This data can be integrated with the data from other partnerships to provide a data base covering the entire nation. This effort will also provide information to evaluate potential pilot sequestration projects in the West Coast Region. The project will promote cooperation among stakeholders and ensure public acceptance of CO_2 sequestration, should that become necessary.

PARTNERS

California Energy Commission
Advanced Resources International
Aera
Automated Geogrpahic Reference Center
British Petroleum
California Dept of Forestry and Fire Protection
California Dept of Oil, Gas and Geothermal Resources
California Geologic Survey
California Polytechnic Institute
California State University at Bakersfield
ChevronTexaco
Clean Energy Systems
ConocoPhillips
Electricity Innovation Institute
Electric Power Research Institute
EPA-California
KinderMorgan
Lawrence Berkeley National Labs
Lawrence Livermore National Labs
Massachusetts Institute of Technology
M. Theo Kearney Fdn of Soil Science
Nevada Bureau of Mine and Geology
Nexant Inc.
Occidental Petroleum
Oregon Department of Forestry
Pacific Forest Trust
Salt River Project
San Francisco Dept of the Environment
Science Strategies
SFA Pacific
Shell
Sierra Pacific Resources
Stanford Global Climate Change Program
Terralog Technologies
TransAlta
Washington State DNR
Western Governors Association
Western States Petroleum Association
Winrock International
Oklahoma Gas and Electric
Oxy Permian Ltd.
PacifiCorp
Public Service Co. of New Mexico
Tucson Electric Power Company
WERC
Wyoming State Geological Survey
Yates Petroleum Corporation

Proj252.pmd

PROJECT facts

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

Sequestration

02/2004

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

John Litynski
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-1339
john.litynski@netl.doe.gov

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

BIG SKY CARBON SEQUESTRATION PARTNERSHIP

Background

The U.S. Department of Energy has selected the seven partnerships of state agencies, universities, and private companies that will form the core of a nationwide network that will help determine the best approaches for capturing and permanently storing gases that can contribute to global climate change. All together, the partnerships include more than 140 organizations, spanning 33 states, three Indian nations, and two Canadian provinces.

The seven partnerships will develop the framework needed to validate and potentially deploy carbon sequestration technologies. They will evaluate and determine which of the numerous sequestration approaches that have emerged in the last few years are best suited for their specific regions of the country. They will also begin studying possible regulations and infrastructure requirements that would be needed should climate science indicate that sequestration be deployed on a wide scale in the future.

PARTNERS

Montana State University

Boise State University

Confederated Salish and Kootenai Tribes

Environmental Financial Products

EnTech Strategies, LLC

Idaho National Engineering and Environmental Laboratory

Los Alamos National Laboratory

Montana Governor's Carbon Sequestration Working Group

National Carbon Offset Coalition

Nez Perce Tribe

South Dakota School of Mines and Technology

Texas A&M University

The Sampson Group

University of Idaho

Description

The Big Sky Carbon Sequestration Partnership (BSCSP), led by Montana State University, Bozeman, MT, will identify and catalogue CO_2 sources and promising geologic and terrestrial storage sites, develop a risk assessment and decision support framework to optimize the area's carbon storage portfolio, enhance market-based carbon storage methods, identify advanced greenhouse gas measurement technologies to improve verification, support voluntary trading and stimulate economic development, call upon community leaders to define carbon-sequestration strategies, and sponsor forums that involve the public. Idaho, Montana and South Dakota are served by this partnership that is comprised of 13 organizations, including the Confederated Salish and Kootenai Tribes and the Nez Perce Tribe.

The region has both industrial and agricultural greenhouse gas (CO_2, methane, and nitrous oxide) emissions from three major sources: fossil fuel power plants, industrial plants, including metals processing, chemical plants, and ethanol production facilities, and agricultural operations, principally feedlots.

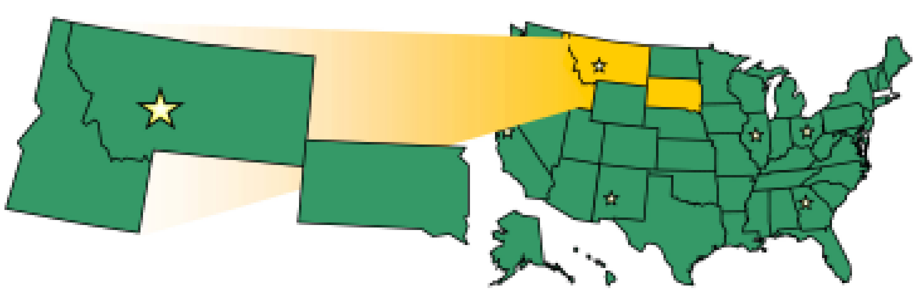
The region encompassed by the partnership includes three major geological terrains with high geologic sequestration potential: the Snake River Plain, the Williston Basin, and the Powder River and Associated Basins. The region contains large forested areas that have great potential to sequester carbon. Cropland and rangeland comprise a sizeable portion of the region and also possess considerable potential for carbon sequestration through improved land management practices. There are a number of abandoned mine sites that have the potential to be reclaimed/reforested to maximize carbon storage.

Primary Project Goal

The overall goal of this project is to identify the most cost effective, technically feasible, and publicly acceptable options for geologic and terrestrial carbon sequestration in the region. The goal in both sequestration options is to optimize the region's carbon storage portfolio, and to improve understanding of geological terrains and ecosystems to assess their long-term potential and effectiveness for storing carbon.

Objectives

- To identify and catalogue sources of CO_2 and promising geologic and terrestrial storage sites.
- To develop a risk assessment and decision support framework to optimize the region's carbon storage portfolio.
- To enhance market based, voluntary approaches to carbon storage.
- To identify and apply advanced greenhouse gas measurement technologies to improve verification protocols, support voluntary trading, and stimulate economic development.
- To engage community leaders to define carbon sequestration implementation strategies.
- To sponsor forums to inform stakeholders and secure input from the public.



Big Sky Regional Carbon Sequestration Partnership - (Region 6)

BUSINESS CONTACT:

Leslie L. Schmidt
406-994-2381
406-994-7951
lschmidt@montana.edu

TECHNICAL CONTACT:

Susan M. Capalbo
406-994-5619
406-994-4152 fax
scapalbo@montana.edu

BUSINESS OFFICE ADDRESS:

309 Montana Hall
Bozeman, MT 59717-2470

COST

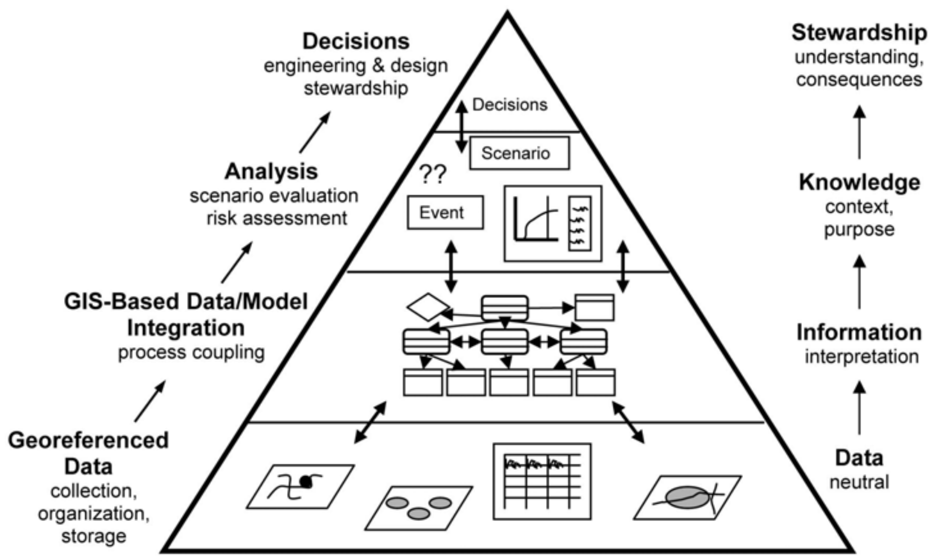
Length of Contract:
24 Months

Total Project Value:
$1,997,889

DOE/Non-DOE Share:
$1,598,279 / $399,610

Benefits

This project will benefit the U.S. by providing a comprehensive assessment of the sources and potential sinks for CO_2 in the Northern Rockies and Great Plains Region. This data can be integrated with the data from other partnerships to provide a database covering the entire nation. This effort will also provide information to evaluate potential pilot sequestration projects in the Northern Rockies and Great Plains Region. The project will promote cooperation among stakeholders and help ensure public acceptance of CO_2 sequestration, should that become necessary.



Proj267.pmd

Sequestration

03/2004

PROJECT facts

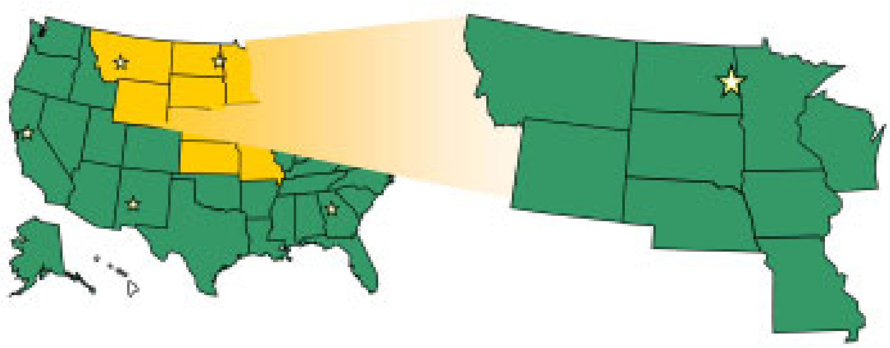
U.S. DEPARTMENT OF ENERGY
OFFICE OF FOSSIL ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

PLAINS CO_2 REDUCTION PARTNERSHIP

Background

As part of a comprehensive effort to assess options for sustainable energy systems, the U.S. Department of Energy has selected the seven partnerships of state agencies, universities, and private companies that will form the core of a nationwide network that will help determine the best approaches for capturing and permanently storing gases that can contribute to global climate change. All together, the partnerships include more than 140 organizations, spanning 33 states, three Indian nations, and two Canadian provinces.

The seven partnerships will develop the framework needed to validate and potentially deploy carbon sequestration technologies. They will evaluate and determine which of the numerous sequestration approaches that have emerged in the last few years are best suited for their specific regions of the country. They will also begin studying possible regulations and infrastructure requirements that would be needed should climate science indicate that sequestration be deployed on a wide scale in the future.



Plains CO_2 Reduction Partnership - (Region 7)

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

John Litynski
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-1339
john.litynski@netl.doe.gov

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

University of North Dakota - Energy & Environmental Research Center (EERC)

Amerada Hess Corporation

Basin Electric Power Cooperative

Bechtel Corporation

Center for Energy & Economic Development (CEED)

Chicago Climate Exchange

Dakota Gasification Company

Eagle Operating, Inc.

Environment Canada

Fischer Oil and Gas, Inc.

Great River Energy

Interstate Oil and Gas Compact Commission

Minnesota Pollution Control Agency

Montana–Dakota Utilities Co.

Montana Department of Environmental Quality

Description

The Plains CO_2 Reduction (PCOR) Partnership, led by the Energy & Environmental Research Center (EERC) at the University of North Dakota, Grand Forks, ND, proposes a three-step approach that involves characterizing technical issues and the public's understanding regarding all aspects of CO_2 sequestration, identifying regional opportunities for sequestration, and detailing action plans to be carried out in Phase II of the Carbon Sequestration Regional Partnership solicitation. The region, which includes North and South Dakota, Minnesota, Wisconsin, Iowa, Missouri, Nebraska and portions of Montana, Wyoming, Saskatchewan, and Manitoba, was chosen based on a similarity in large stationary CO_2 sources and geologic and terrestrial CO_2 sinks, transport considerations for direct CO_2 sequestration, and the presence of two major anthropogenic CO_2 enhanced oil recovery projects.

The region generates a little less than 5% of U.S. CO_2 emissions from 29 coal-fired utilities, 27 ethanol-production facilities, and the Dakota Gasification facility, which together account for about half of the region's CO_2 emissions. The region includes the Williston and Powder River basins. These basins have active or planned sequestration projects related to value added conventional oil or coal bed methane production, as well as recognized potential for sequestration in deep aquifers, depleted hydrocarbon production units, and unminable coal seams. The semiarid, rolling grasslands of the plains dominate the Western portion of the region. They are currently used for grazing and growing small grains. Together with the forested landscape of the Northeast and North, they offer opportunities for testing and verification of soil and vegetative

The PCOR Partnership will be utilizing a screen and funnel approach to determine the best opportunities for carbon sequestration in the region.

terrestrial CO_2 sequestration technologies.

Primary Project Goal

The goal of this project is to develop and implement a partnership in the Northern Great Plains region that can identify cost effective CO_2 sequestration systems for the region and then facilitate and manage the testing of these technologies.

Objectives

- To assess CO_2 sources, sinks, technologies for CO_2 separation, and transportation options within the region.
- To evaluate options and potential opportunities for regional CO_2 sequestration.
- To develop action plans for the implementation of small-scale validation testing of the most promising technologies.
- To promote the implementation of technology for the capture, transport, and storage of anthropogenic fossil fuel combustion CO_2 emissions.
- To raise public awareness regarding carbon sequestration issues and to obtain public input.

The PCOR Partnership had its kickoff meeting on December 11 and 12, 2003. The PCOR Partnership currently has 30 active partners from a broad range of industry, academia, research organizations, federal institutions, and non-governmental organizations.

PARTNERS (continued)

Montana Public Service Commission

Natural Resources Trust

NDIC Oil and Gas Division

Nexant, Inc.

North Dakota Department of Health

North Dakota Geological Survey

North Dakota Industrial Commission (NDIC)

North Dakota Petroleum Council

North Dakota State University

Otter Tail Power Company

Petroleum Technology Transfer Council

Prairie Public Television

Tesoro Refinery

Western Governors Association

BUSINESS CONTACT

Sheryl E. Landis
701-777-5124
701-777-5181 fax
slandis@undeerc.org

TECHNICAL CONTACT

Thomas A. Erickson
701-777-5153
701-777-5181 fax
terickson@undeerc.org

Business Office Address:
15 North 23rd Street
Grand Forks, ND 58203

COST

Length of Contract:
24 Months

Total Project Value:
$2,748,139

DOE/Non-DOE Share:
$1,586,614/$1,161,525

Benefits

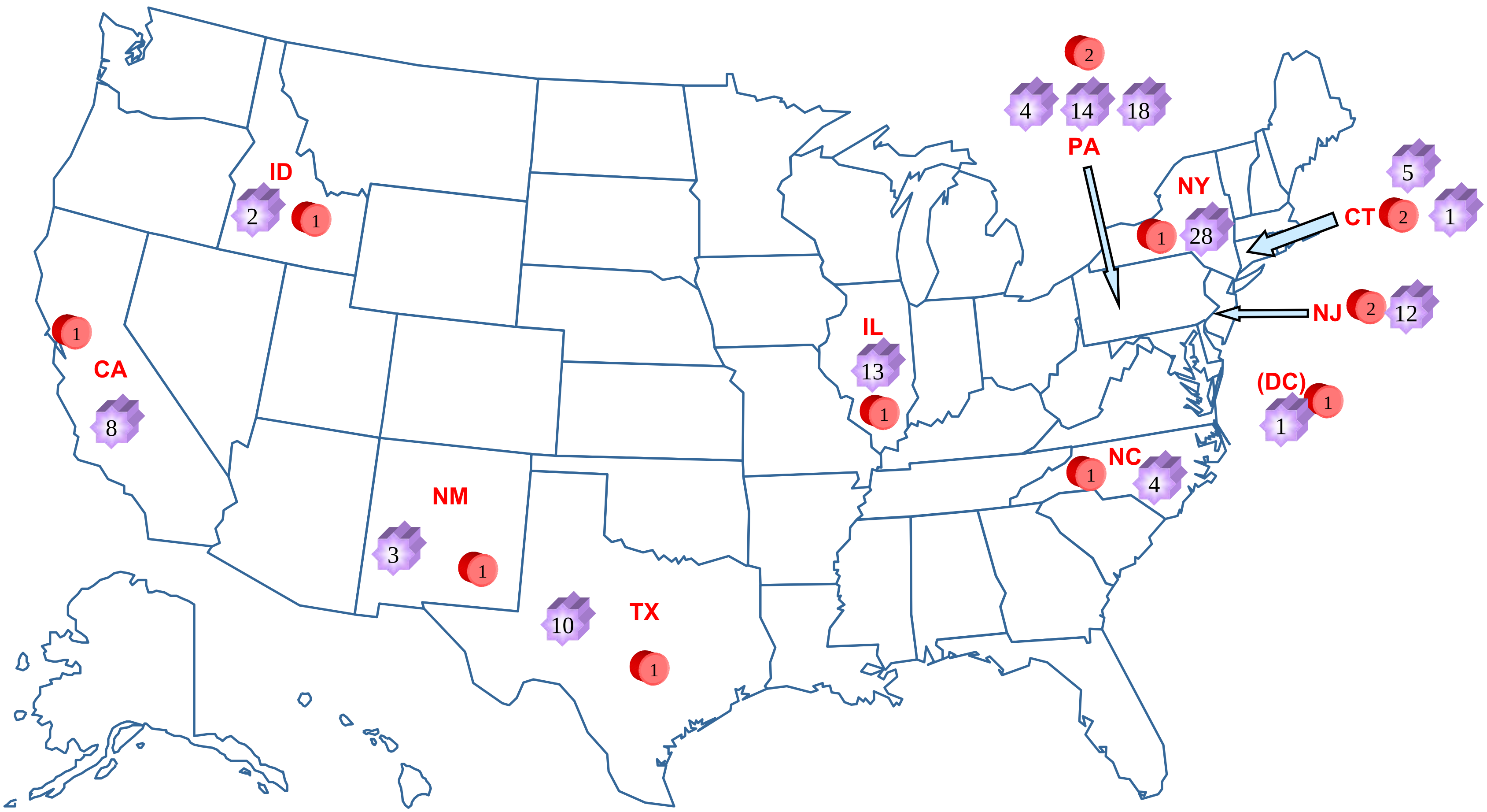
Sequestration is one option to reduce CO_2 emissions and this project will benefit the U.S. by providing a comprehensive assessment of the sources and potential sinks for CO_2 in the Northern Great Plains Region. This data can be integrated with the data from other partnerships to provide a data base covering the entire nation. This effort will also provide information to evaluate potential pilot sequestration projects in the Northern Great Plains Region. The project will promote cooperation among stake holders and help ensure an informed public should CO_2 sequestration become an option. Analysis of existing EOR projects in the region will also provide valuable data to increase understanding of this option for CO_2 sequestration.

Capture of CO_2

Page left blank to accommodate 2-sided printing

Capture of CO_2 Projects

LEGEND
Number of Capture of CO_2 Projects
Congressional District



*Doesn’t include NETL

Capture of CO_2 Congressional Districts List

Project Title	Primary Contractor	Congressional District
Advanced Oxyfuel Boilers and Process Heaters for Cost Effective CO_2 Capture and Sequestration	Praxair, Inc.	NY28
CO_2 Hydrate Process for Gas Separation from a Shifted Synthesis Gas Stream	Nexant	CA08
A Collaborative Project to Develop Technology for Capture and Storage of CO_2 from Large Combustion Sources	BP Corporation	DC01
Carbon Dioxide Capture from Flue Gas Using Dry Regenerable Sorbents	Research Triangle Institute	NC04
CO_2 Selective Ceramic Membrane for Water-Gas-Shift Reaction with Simultaneous Recovery of CO_2	Media and Process Technology Inc.	PA04
CO_2 Separation Using a Thermally Optimized Membrane	INEEL	ID02
CO_2 Separation Using a Thermally Optimized Membrane	LANL	NM03
CO_2 Capture for PC-Boiler Using Flue-gas Recirculation: Evaluation of CO_2 Capture/Utilization/Disposal Options	ANL	IL13
Greenhouse Gas Emissions Control by Oxygen Firing in Circulating Fluidized Bed Boilers	ALSTOM Power, Inc.	CT01
Carbon Dioxide Capture by Absorption with Potassium Carbonate	University of Texas at Austin	TX10
An Integrated Modeling Framework for Carbon Management Technologies	Carnegie Mellon University	PA14
Conceptual Design of Oxygen-Based PC Boiler	Foster Wheeler Development Corporation	NJ11
Conceptual Design of Optimized Fossil Energy Systems with Capture and Sequestration of CO_2	Princeton University	NJ12
Combined Power Generation and Carbon Sequestration Using a Direct Fuel Cell	FuelCell Energy, Inc.	CT05

(NETL projects not included)

Capture of CO_2

Technology Target
- Complete pilot plant testing of precombustion decarbonization systems
- Complete pilot plant testing of oxy fuel concept
- Complete pilot plant testing of promising post-combustion technology
- Cost-share power plant retrofit with advanced CO_2 capture technology

Commercialization

Outcomes
- Efficient low-cost electricity and hydrogen production with low GHG emissions
- Commercially viable options for retrofit/repower of existing plants to reduce CO_2 emissions

Open Category
CMU – Modeling framework for carbon management
Princeton Univ – Conceptual design – capture and Seq of CO_2
ANL – Evaluation of CO_2 Capture options

Pre Combustion
- Decarbonization
- Advanced sorbents Hybrid sorbent/membrane systems

NEXANT - CO_2 Hydrate process for gas separation
NETL – Sorbent development for CO_2 separation and removal
MPTC – Selective ceramic membrane
BP – CO_2 Capture project
– **Eltron**
- Membrane WGS
– **Air Products**
- Sorption Enhanced WGS

Oxyfuel
- O_2 – selective membranes Advanced cooling cycles Compact boiler

Praxair – Advanced oxy-fuel boilers and process heaters
Alstom Power – Oxygen firing in CFB boiler
Foster-Wheeler – Technical and economic viability of oxygen-enriched PC – fired boiling system with CO_2 sequestration

Post Combustion
- Chemical and physical sorbents
- Hybrid sorbents/membrane system
- Gas/liquid contactors

RTI – Dry regenerable CO_2 sorbents
NETL – CO_2 scrubbing with regenerable sorbents
NETL – Novel Amine-enriched sorbents
NETL – Modular CO_2 Capture facility
UT Austin – Adsorption with K_2CO_3/Piperazine
INEEL, LANL- High-Temperature polymer membrane
FuelCell Energy – Direct fuel cell

Page left blank to accommodate 2-sided printing

Project Title	Primary Contractor	Fact Sheet Listing
Advanced Oxyfuel Boilers and Process Heaters for Cost Effective CO_2 Capture and Sequestration	Praxair, Inc.	C-6
CO_2 Hydrate Process for Gas Separation from a Shifted Synthesis Gas Stream	Nexant	C-8
A Collaborative Project to Develop Technology for Capture and Storage of CO_2 from Large Combustion Sources	BP Corporation	C-10
Carbon Dioxide Capture from Flue Gas Using Dry Regenerable Sorbents	Research Triangle Institute	C-14
CO_2 Selective Ceramic Membrane for Water-Gas-Shift Reaction with Simultaneous Recovery of CO_2	Media and Process Technology Inc.	C-16
CO_2 Separation Using a Thermally Optimized Membrane	LANL & INEEL	C-18
CO_2 Capture for PC-Boiler Using Flue-gas Recirculation: Evaluation of CO_2 Capture/Utilization/Disposal Options	ANL	C-20
Greenhouse Gas Emissions Control by Oxygen Firing in Circulating Fluidized Bed Boilers	ALSTOM Power, Inc.	C-22
Carbon Dioxide Capture by Absorption with Potassium Carbonate	University of Texas at Austin	C-24
An Integrated Modeling Framework for Carbon Management Technologies	Carnegie Mellon University	C-26
Conceptual Design of Oxygen-based PC Boiler	Foster Wheeler Corporation	C-30
Conceptual Design of Optimized Fossil Energy Systems with Capture and Sequestration of CO_2	Princeton University	C-32
Sorbent Development for Carbon Dioxide Separation and Removal – PSA & TSA	NETL	C-34
CO_2 Scrubbing with Regenerable Sorbent*	NETL	C-36
Novel Amine-Enriched Sorbents*	NETL	C-38
NO_2 & NOx and CO_2 Removal with Aqua Ammonia*	NETL	C-40
Modular CO_2 Capture Facility	NETL	C-42
Combined Power Generation and Carbon Sequestration Using a Direct Fuel Cell	FuelCell Energy, Inc.	C-44

(BP CCP and UCR projects not included)

* Factsheet Under Development

Page left blank to accommodate 2-sided printing

PROJECT facts

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

Sequestration

07/2004

ADVANCED OXYFUEL BOILERS AND PROCESS HEATERS FOR COST EFFECTIVE CO_2 CAPTURE AND SEQUESTRATION

Background

Reducing CO_2 from large stationary combustion systems has been targeted as a cost efficient means of reducing the emission of greenhouse gases from fossil fuel combustion systems. A number of concepts exist or have been proposed to reduce emissions, including fuel switching, efficiency improvements, CO_2 capture from conventional flue gas streams, and oxy-fuel fired systems with CO_2 capture. Switching fuels from coal to lower carbon fuels such as natural gas can reduce emissions, but severely restricts the nation's fuel flexibility and underutilizes the most abundant natural resource in the United States. Enhancing site efficiency by building natural gas combined cycle plants or making efficiency improving plant modifications can also significantly reduce emissions of greenhouse gases. However, these options simply do not provide enough reduction in emissions to mitigate the growing problem of global warming.

One economical solution to overcome these problems is to switch to oxy-fuel combustion. The use of oxygen in place of air results in a much lower volume of flue gas, which enhances thermal efficiency, thereby lowering CO_2 emissions. This four-year project will advance the integration of oxygen transport membranes (OTM) into oxyfired boilers from the bench scale to the point-of-readiness for engineering scaleup. The development of this novel boiler will require both Praxir's expertise in OTM development and oxy-fuel combustion and the experience of Alstom Power in boiler development and manufacturing. These highly efficient boilers, through incorporation of lower cost OTM oxygen generation technology, can economically provide a significant portion of the required reductions in greenhouse gases.

Primary Project Goal

The object of this project is to develop and demonstrate the integration of a novel ceramic oxygen transport membrane (OTM) with the combustion process to enhance boiler efficiency and carbon dioxide recovery.

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Timothy Fout
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880
304-285-1341
Timothy.Fout@netl.doe.gov

John Sirman
Praxair, Inc.
175 East Park Drive
P.O. Box 44
Tonawanda, NY 14151-0044
716-879-7395
John_Sirman@praxair.com

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

ADVANCED OXYFUEL BOILERS AND PROCESS HEATERS FOR COST EFFECTIVE CO_2 CAPTURE AND SEQUESTRATION

PROJECT PARTNERS

Praxair
Alstom Power

COST

Total Project Value:	$5,836,487
DOE:	$4,085,537
Non-DOE Share:	$1,750,950

Objectives

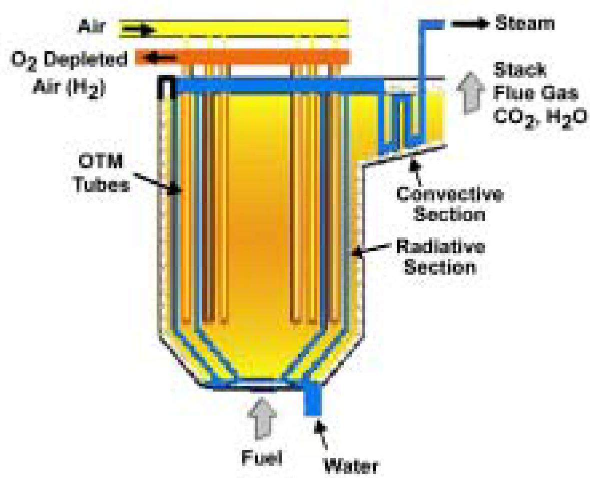
- Identify the optimal design based on technical performance; identify and demonstrate the most promising OTM materials for the integrated system; and develop a conceptual design for a laboratory scale boiler simulator.
- Perform economic analyses throughout the program to ensure the novel boiler will bring economic value to both the industrial customers and to the participating companies.
- Complete project by December 2005.

Accomplishments

A ceramic membrane and seal assembly have been developed for thermal integration between the high temperature membrane and the combustion process. Alstom Power has initiated modeling studies to understand and predict the combustion characteristics of oxy-fuel technology. Current efforts are focusing on laboratory scale evaluations for integration of OTM with the combustion process.

Benefits

The development of a novel oxy-fuel boiler will significantly reduce the complexity of CO_2 capture, drastically reduce the cost of carbon sequestration, and offer increased thermal efficiency and reduced pollution emissions. This highly efficient boiler will economically provide a significant portion of the required reductions in greenhouse gases. Gasification plants which integrate OTM technology will have higher efficiency, lower cost of electricity, and lower emissions of pollutants compared to using a conventional cryogenic air separation unit.



Praxair Advanced Boiler

Proj197.pmd

PROJECT facts

Sequestration

03/2004

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

CO_2 HYDRATE PROCESS FOR GAS SEPARATION FROM A SHIFTED SYNTHESIS GAS STREAM

Background

One approach to decarbonizing coal is to gasify it to form fuel gas consisting predominately of carbon monoxide and hydrogen. This fuel gas is sent to a shift conversion reactor where carbon monoxide reacts with steam to pro-duce carbon dioxide and hydrogen. After scrubbing the carbon dioxide from the fuel, an almost pure hydrogen stream is left which can be burned in a gas turbine or used to power a fuel cell with essentially zero emissions. However, for this approach to be practical, it will require an economical means of separating carbon dioxide from mixed gas streams. Since viable options for sequestration or reuse of carbon dioxide are projected to involve transport through pipelines and/or direct injection of high pressure carbon dioxide into various repositories, a process that can separate carbon dioxide at high pressures and minimize recompression costs will offer distinct advantages. This project addresses the issue of carbon dioxide separation from shifted synthesis gas at elevated pressures.

The project is concerned with development of the low temperature SIMTECHE process. This process utilizes the formation of carbon dioxide hydrates to remove CO_2 from a gas stream. Many people are familiar with methane hydrates but are unaware that, under the proper conditions, CO_2 forms similar hydrates. In Phase 1, a conceptual process flow scheme was developed. The thermodynamic limits of such a process were confirmed by equilibrium hydrate formation experiments for shifted synthesis gas com-positions. Performance projections were then made for a few selected process configurations, and encouraging preliminary economics were developed.

Primary Project Goal

The goal of this project is to construct and operate a pilot-scale unit utilizing the hydrate process for CO_2 separation.

Objectives

The program is currently in phase 2 of a 3-phase plan. The objectives of phase 2 are: (1) carry out further laboratory-scale tests of the CO_2 hydrate concept, including extended continuous-flow tests and component tests; (2) conduct an engineering analysis of the concept, and develop updated estimates of the process performance and cost of carbon control; (3) use data developed in the lab to design and build a pilot plant using a slipstream in an operating IGCC plant. Phase 3 will consist of a pilot demonstration of the process in the IGCC plant.

CONTACT POINTS

Scott M. Klara
Sequestration Product Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Jose Figueroa
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4966
jose.figueroa@netl.doe.gov

Samuel S. Tam
Nexant
45 Fremont Street
P.O. Box 193965
San Francisco, CA 94119
415-768-9472
713-235-3037 fax
sstam@nexant.com

CO_2 Hydrate Process for Gas Separation from a Shifted Synthesis Gas Stream

PROJECT PARTNERS

Nexant
Los Alamos National Laboratory (LANL)
SIMTECHE

COST

Total Project Value:
$15,993,621

Nexant
DOE Share: $9,076,621
Non-DOE Share: $0

Los Alamos National Laboratory
DOE: $6,917,000
Non-DOE Share: $0

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

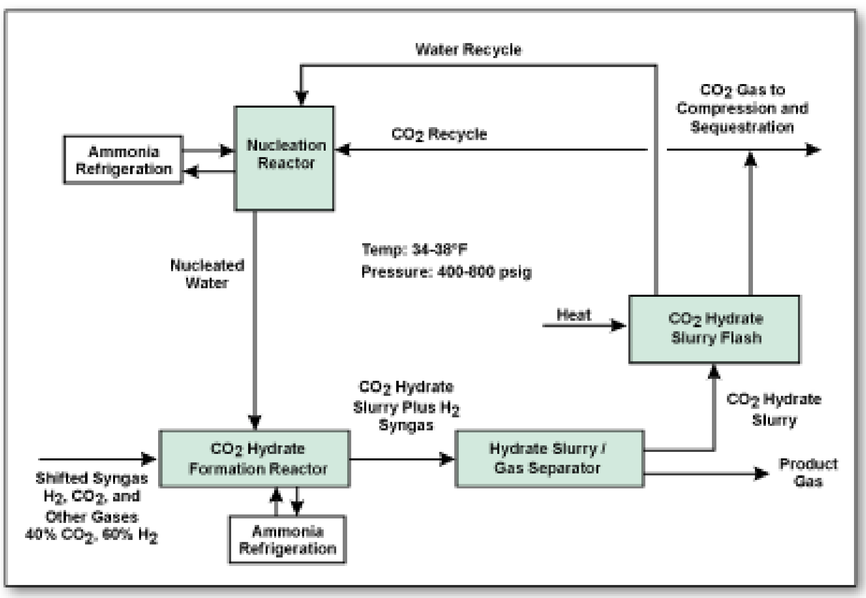
Accomplishments

A bench-scale flow system for the continuous production of carbon dioxide hydrates was assembled, and operational issues associated with continuous hydrate production were resolved. The technical feasibility of the SIMTECHE process was thereby demonstrated. The enhancement of carbon dioxide hydrate formation and separation by the presence of gaseous and/or liquid promoters was also demonstrated in the laboratory.

Benefits

The hydrate process will provide a high pressure/low temperature system for separating CO_2 from shifted synthesis gas in an economical manner. The process can be adapted to an existing gasification power plant for CO_2 separation in the production of synthesis gas.

Overall, the process will result in a residual concentrated stream of hydrogen capable of fueling zero-emission power plants of the future and a concentrated CO_2 stream available for use or sequestration.



Conceptual Process Block Flow Diagram of a CO_2 Hydrate Process

Proj196.pmd

PROJECT facts

Sequestration

06/2003

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

CO_2 Capture Project: Collaborative Technology Development Project for Next Generation CO_2 Separation, Capture and Geologic Storage

CONTACT POINTS

Scott M. Klara
Sequestration Product Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

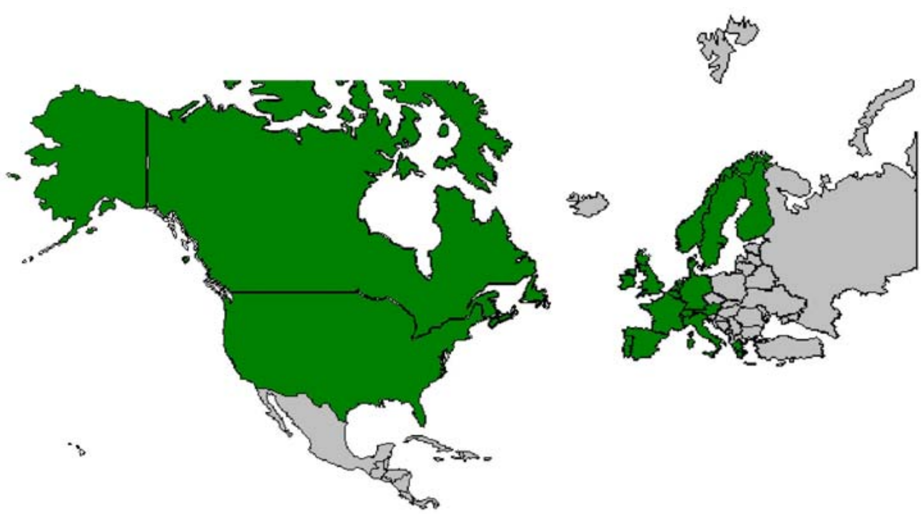
David Hyman
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-6572
david.hyman@netl.doe.gov

Gardiner Hill
CCP Program Director
BP Corporation
1776 I Street, Suite 934
Washington, DC 20006
202-756-1324
hill@bp.com

Helen Kerr
CCP Project Manager
BP Corporation
1776 I Street, Suite 934
Washington, DC 20006
202-756-1323
kerrhr@bp.com 2

Background

DOE has joined with eight major international energy companies to sponsor the CO_2 Capture Project (CCP) with the goal of developing breakthrough technologies aimed at substantially reducing the cost of CO_2 capture and geologic storage. The CCP consortium is operated by BP and its members include ChevronTexaco, ENI, Norsk Hydro, PanCanadian, Shell, Statoil, and Suncor. In addition to the U.S. program, the CCP is comprised of separate, but complimentary projects which are also being sponsored by the European Union, and Norway. The total value of the CO_2 Capture Project, including international components, is $25 million.



Global participation of International Leading Energy Companies

Participating Phase I Technology Providers

Air Products & Chemicals, Inc.

Colorado School of Mines

Eltron Research Corporation

Energy Resource Centre of the Netherlands (ECN)

Fluor Daniel, Inc.

Idaho National Engineering & Environmental Laboratory

Lawrence Berkeley National Laboratory

Lawrence Livermore National Laboratory

McDermott Technology, Inc.

Netherlands Institute of Applied Geosciences

Oakridge National Laboratory

Scientific Monitor

SINTEF

Stanford University

Stanford Research Institute

TDA Research, Inc.

Texas Tech University

Tie-Line Technology

University of Cincinnati

Utah State University

The project schedule spans a 3-year period and is divided into two phases. Phase 1 represents the initial technology development period in which various promising avenues of R&D are pursued. Phase 2 will involve reprioritizing the R&D activities based on Phase 1 findings and then continuing with development of the most promising technologies.

Objectives

The strategic objective of the proposed project is to work with selected technology providers to develop new, breakthrough technologies, to the proof-of-feasibility stage, to reduce the cost of CO_2 separation, capture, transportation and sequestration from flue gases by one-half over today's best available technology for existing facilities, and by three-quarters for new facilities, by the end of 2003. The tactical objectives of the project are to:

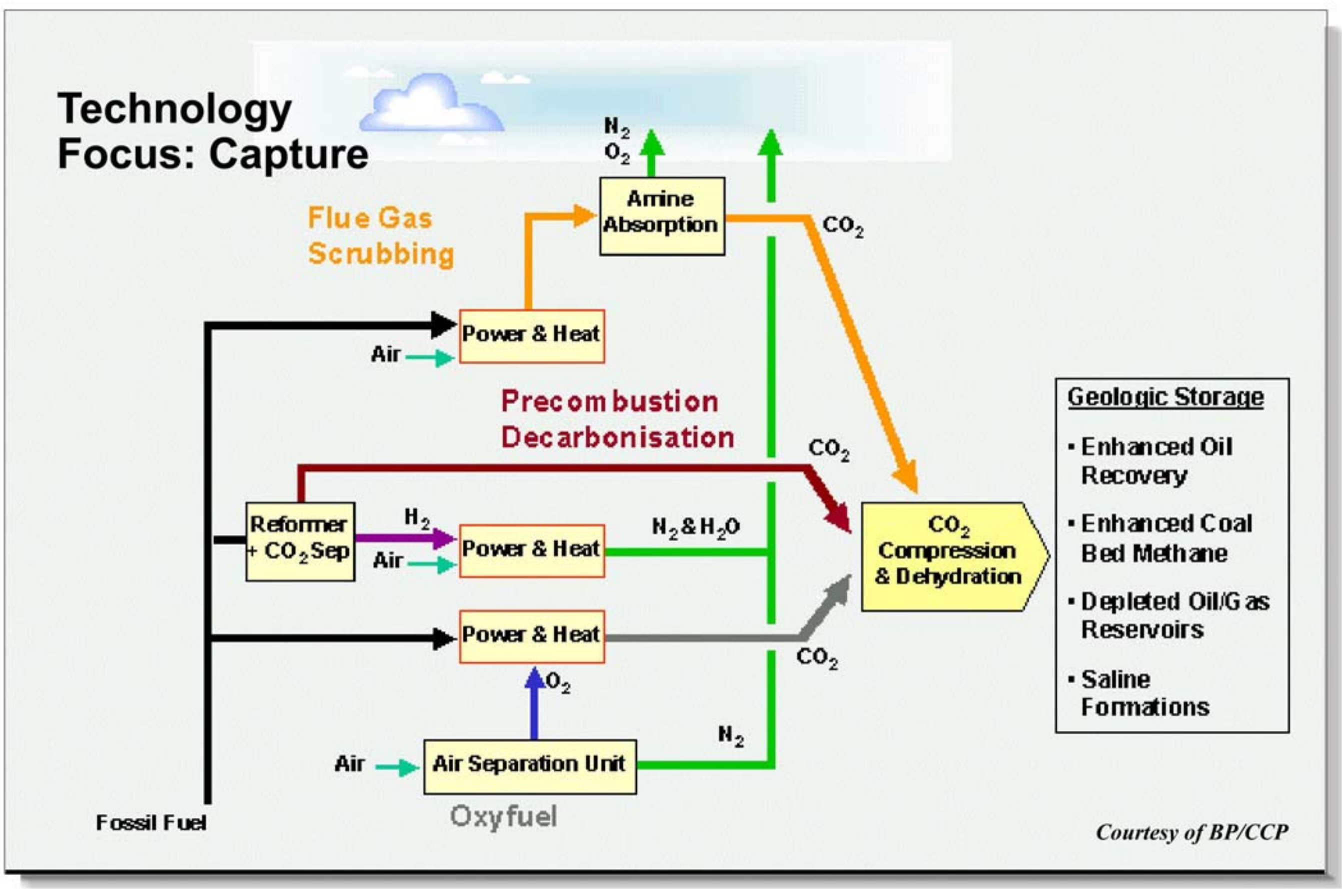
- Perform "benchtop" R&D (engineering studies, computer modeling, laboratory experiments) to prove the feasibility of advanced CO_2 separation and capture technologies, specifically targeting post-combustion methods, pre-combustion decarbonization, and oxyfuel.
- Develop guidelines for maximizing safe geologic sequestration, for measuring/verifying sequestration volumes, and for assessing and mitigating sequestration risks.
- Demonstrate to external stakeholder that CO_2 storage is safe, measurable, and verifiable.
- Develop technologies to the "proof of concept" stage by 2003/2004 and achieve at least one large-scale application by 2010

Benefits

The CCP team collectively accounts for approximately 32% of all oil and 17% of all gas production in the U.S., and 28% and 17% of oil and gas production respectively from OECD countries,. This team not only represents a significant market for the technologies to be developed, it is in the unique position of also operating and utilizing many of the geologic sinks needed to sequester the CO_2. These existing commercialization pathways will facilitate rapid industrial deployment of the new technologies developed under this project. Using conservative assumptions, the technology developed in the project could reduce the emissions of the CCP participants by 10 million tonnes of carbon per year (11 million tons per year). When applied more broadly in industry, the technology could reduce emissions by up to 140 million tonnes of carbon per year.

The potential scientific breakthroughs that could result from this project include:

- New solvents to reduce CO_2 separation costs.
- Improved CO_2 /H_2 absorption membranes.
- Integrated H_2 generation processes.
- Advanced oxyfuel boiler designs.
- An enhanced understanding of controls and requirements for geologically sequestering CO_2.



Flow diagram of various CO_2 capture and storage technologies

CO_2 Capture Project: Collaborative Technology Development Project for Next Generation CO_2 Separation, Capture and Geologic Storage

PARTNERS

National Energy Technology Laboratory

BP Corporation

ChevronTexaco

Norsk Hydro

Shell

Statoil

Suncor Energy

Pan Canadian

ENI

COST

Total Project Value	$9,994,165
DOE	$4,995,000
Non-DOE Share	$4,999,165

CUSTOMER SERVICE

800-553-7681

WEBSITE

www.netl.doe.gov

In addition to reducing technology costs, domestic energy security will also benefit. The proposed project develops lower cost separation and capture technology, which when combined with value-added geologic sequestration opportunities (EOR and ECBM) provides industry with a market-driven mid-term option for reducing CO_2 emissions while continuing to use fossil fuels. Additional benefits include a significant increase in the production of domestic oil and natural gas which improves U.S. energy security. It is estimated that 12 billion barrels (1.9 billion m 3) of incremental oil and 31 Tcf (0.9 Tm 3) of incremental gas is technically recoverable via these processes. Although the technology will enhance viability of CO_2 EOR, the focus of the R&D will be on new technologies to maximize the amount of CO_2 stored and the assurance and verification of sequestered volumes.

Proj185.pmd

PROJECT facts

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

Sequestration

11/2004

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Jose Figueroa
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4966
jose.figueroa@netl.doe.gov

Raghubir Gupta
Research Triangle Institute
3040 Cornwallis Road
P.O. Box 12194
Research Triangle Park, NC 27709-2194
919-541-8023
919-541-8000 fax
gupta@rti.org

Carbon Dioxide Capture from Flue Gas Using Dry Regenerable Sorbents

Background

Currently available commercial processes to remove CO_2 from waste gas streams are costly. Research Triangle Institute, working with Church and Dwight, Inc., is developing an innovative process for CO_2 capture that employs a dry, regenerable sorbent. The process is cyclic in that the sorbent first captures the CO_2, is regenerated to yield a concentrated stream of CO_2, and then recycled to the absorption/adsorption step. Although, the proposed process can be used to remove CO_2 from flue gas, it can also be used to capture CO_2 from gasification streams at high temperature.

Sorbents being investigated, primarily alkali carbonates, are converted to bicarbonates through reaction of carbon dioxide and water vapor. Sorbent regeneration produces a gas stream containing only CO_2 and water. The water may be separated out by condensation to produce a pure CO_2 stream for subsequent use or sequestration.

Primary Project Goal

The goal of this project is to develop a simple, inexpensive process to separate CO_2 as an essentially pure stream from a fossil fuel combustion system using a regenerable sorbent.

Objectives

To develop a technology that is

- Applicable to both coal and natural gas-based power plants.
- Applicable as a retrofit to existing plants, as well as to new power plants.
- Compatible with the operating conditions in current power plant configurations.
- Able to handle flue gas containing contaminants such as SO_2, HCl, particles, and possibly heavy metals, such as Hg.
- Relatively simple to operate.
- Significantly cheaper than currently available technologies.

PROJECT PARTNERS

RTI

Church and Dwight, Inc.

Louisiana State University

COST

Total Project Value:	$1,050,889
DOE:	$ 812,285
Non-DOE Share:	$ 238,604

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

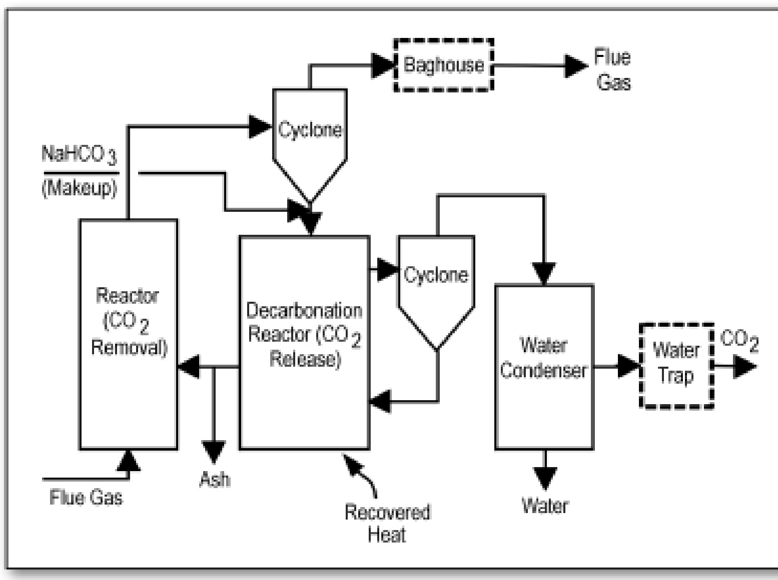
www.netl.doe.gov

Accomplishments

The sorbent material has been well characterized and analyzed for chemical composition. Testing has confirmed that the reaction rate and achievable CO_2 capacity of sodium carbonate decreases with increasing temperature and that the global rate of reaction of sodium carbonate to sodium bicarbonate increases with an increase in both CO_2 and H_2O concentrations. It has been shown that capture of 25% of the CO_2 will not require any additional power. Future efforts will be aimed at optimizing the process to capture additional CO_2 without requiring additional power.

Benefits

This technology will provide conventional pulverized-coal fired power plants, natural gas-fired combined cycle plants, and advanced power generation systems with a less costly process to remove CO_2 from the flue gas. The ability to operate a CO_2 removal system at higher temperatures is more efficient that low temperature systems.



Conceptual Transport Reactor System

This configuration is an attractive treatment option for flue gas from power plants employing wet FGD and for flue gas from natural gas-fired systems.

Proj198.pmd

Sequestration

07/2004

PROJECT
facts

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

CO_2 SELECTIVE CERAMIC MEMBRANE FOR WATER-GAS-SHIFT REACTION WITH SIMULTANEOUS RECOVERY OF CO_2

Background

The water-gas-shift (WGS) reaction, $CO + H_2O \leftrightarrow H_2 + CO_2$, is used to increase the hydrogen content of synthesis gas. However, this reaction is equilibrium limited. One approach for overcoming this limitation is to carry out the reaction in a reactor with walls that are CO_2 permeable. This continuously removes CO_2 from the system and allows the reaction to continue.

This project involves the development of a technique for depositing hydrotalcite onto a ceramic membrane suitable for implementing the reactive separation concept with the WGS reaction in integrated gasification combined cycle (IGCC) systems. The membranes are being developed using available sol gel and chemical vapor deposition (CVD) preparation techniques. The hydrotalcite is permeable to CO_2 but plugs the pores, preventing passage of other gases. The hydrothermal and chemical stability in a simulated WGS reaction environment will be evaluated to confirm the inert material properties of the ceramic membrane. Then, a membrane reactor (MR) study will be conducted to demonstrate the benefit offered by this membrane. Finally, process feasibility will be demonstrated in a test module, and an economic evaluation will be performed to estimate the positive effect of using a WGS-MR in IGCC coal-fired power plants.

Primary Project Goal

The primary objective of this program is to develop a defect-free hydrotalcite membrane for selective CO_2 removal that will be effective in the water-gas-shift reaction environment, i.e., 300 to 600°C and in the presence of steam.

Objectives

- Conduct a screening study to select an optimal material for developing a membrane and determine the optimum operating conditions in terms of temperature and steam content of the gas for selective CO_2 removal (good thermal, hydrothermal and chemical stability).
- Fabrication of the desired membrane in tubular geometry and verification of the feasibility of CO_2 separation along with the conversion enhancement.

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Paul K.T. Liu
Media and Process Technology Inc.
1155 William Pitt Way
Pittsburgh, PA 15238
412-826-3721
412-826-3720 fax
mandpmain@aol.com

David Lang
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940\
Pittsburgh, PA 15236
412-386-4881
David.Lang@netl.doe.gov

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

CO_2 Selective Ceramic Membrane for Water-Gas-Shift Reaction with Simultaneous Recovery of CO_2

PROJECT PARTNERS

Media and Process Technology Inc.

University of Southern California

COST

Total Project Value:	$900,000
DOE:	$720,000
Non-DOE Share:	$180,000

Accomplishments

Results from the TGA/MS studies show that the hydrotalcite material exhibits a high degree of CO_2 reversibility. Insignificant adsorption of water has been observed at higher temperatures (greater than 200ºC). Based on these results, the conclusion is that the hydrotalcite is an ideal candidate material for high temperature gas separations requiring hydrothermal stability.

Benefits

This combined shift reaction and CO_2 separation system project will produce a hydrogen rich gas which is at high pressure, high temperature and contains significant quantities of steam making it highly suitable for direct firing in a gas turbine with high efficiency. The use of an improved WGS-MR with CO_2 recovery capability is ideally suited to integration into the IGCC) power generation system. Thus, the hydrogen (high pressure and CO_2 -free) pro-duced from the IGCC can be used either as a product for power generation via a turbine or a fuel cell, or as a reactant for fuels and chemicals production.

Proj195.pmd

PROJECT facts

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

Sequestration

03/2004

CO_2 SEPARATION USING A THERMALLY OPTIMIZED MEMBRANE

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Jose D. Figueroa
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4966
Jose.Figueroa@netl.doe.gov

Philip Goldberg
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-5806
philip.goldberg@netl.doe.gov

Jennifer S. Young
Los Alamos National Laboratory (LANL)
P.O. Box 1663
Los Alamos, NM 87545
505-667-7328; 505-667-8109 fax
jyoung@lanl.gov

Background

The last decade has witnessed a dramatic increase in the use of polymer membranes as an effective, economic, and flexible tool for many commercial gas separations, including air separation, the recovery of hydrogen from nitrogen, carbon monoxide, and methane mixtures, and the removal of carbon dioxide from natural gas. In each of these applications, processes with high fluxes and excellent selectivities have relied on glassy polymer membranes, which separate gases based on both size and solubility differences. To date, however, membrane technology has focused on optimizing materials for near ambient conditions.

Los Alamos National Laboratory (LANL), in collaboration with Idaho National Engineering and Environmental Laboratory (INEEL), will develop a high-temperature polymer membrane that will exhibit permselectivity for CO_2 an order of magnitude higher than current polymer membranes. The project will focus on the separation of CO_2/CH_4, CO_2/N_2 and H_2/CO_2gas pairs, which represent separations that are industrially and environmentally important. Capitalizing on the interplay between polymer structure and gas diffusion at temperatures between 100°C and 400°C will lead to structures with unprecedented stability and selectivity. By increasing the rigidity of the thermally stable polybenzimidazole (PBI) backbone and using semi-interpenetrating polymer networks, the researchers will inhibit interchain mobility and control diffusion pathways. This approach will lead to polymer membranes with tunable permeability, polymer modification and casting protocols. Collaboration with the University of Colorado involves the development of a new technique to simultaneously measure compaction and permeation of the new materials. This type of measurement will provide great insight into the long-term performance of the membranes from short-term laboratory tests. Industrial collaboration with Pall Corporation provide the project with direct involvement of world leaders in membrane production.

Primary Project Goal

The purpose of this project is to develop polymeric-metallic membranes for carbon dioxide separation that operate under a broad range of industrially relevant conditions not accessible with present membrane units.

PBI coated metal

CONTACT POINTS (continued)

Eric Peterson
Idaho National Engineering and Environmental Laboratory (INEEL)
Bechtel BWXT Idaho, LLC
P.O. Box 1625
Idaho Falls, ID 83415
208-526-1521
esp@inel.gov

PROJECT PARTNERS

LANL

INEEL

Pall Corporation

University of Colorado

Shell Oil Company

COST

Total: $1,400,360

DOE Share: $1,400,360

Non-DOE Share: $0

WEBSITE

www.netl.doe.gov

Objectives

The major objective is the development of polymeric materials that achieve the important combination of high selectivity, high permeability, and mechanical stability at temperatures significantly above 25°C and pressures above 10 bar.

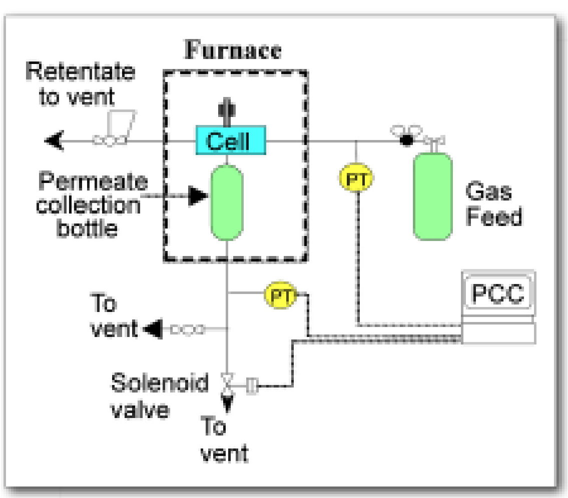
Accomplishments

Progress to date includes the first ever fabrication of a polymeric-metallic membrane that is selective from room temperature to 400°C. This achievement represents the highest demonstrated operating temperature at which a polymeric based membrane has successfully functioned.

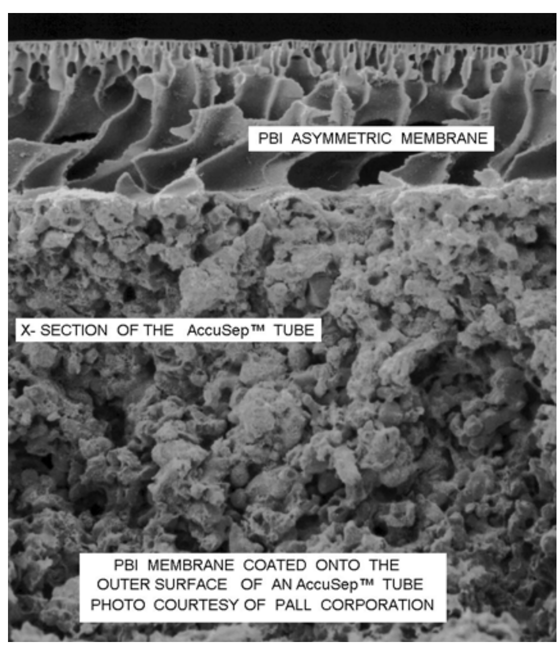
We have also fabricated a shell and tube module of the PBI coated on an AccuSepä tube. This module has significant selectivity at room temperature. Further testing is in progress to demonstrate performance at elevated temperatures using simulated process gases. Additionally, the synthesis efforts of this project have resulted in the first modified polybenzamidizoles that are soluble in common organic solvents. The pendant group modifications of the polymer include both organic and hybrid organic-inorganic systems that provide additional polymer flexibility, ability to fit complex shapes, and modified gas transport properties. Finally, a technique has been developed that has enabled the first-ever simultaneous measurements of gas permeation and membrane compaction at elevated temperatures. This technique provides a unique approach to the optimization of long-term membrane performance under challenging operating conditions based on short-term laboratory studies.

Benefits

The development of high temperature polymeric-metallic composite membranes for carbon dioxide separation at temperatures of 100-450°C and pressures of 10-150 bar will provide a pivotal achievement with both economic and environmental benefits. This technology could further reduce the cost of CO_2 sequestration by providing a CO_2 stream at higher pressures than existing technologies, thereby reducing compression costs significantly.



Membrane Testing Equipment



PBI coated AccuSepä tube used for module development

Proj194.pmd

PROJECT facts

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

Sequestration

10/2003

CO_2 CAPTURE FOR PC-BOILER USING FLUE-GAS RECIRCULATION: EVALUATION OF CO_2 CAPTURE/UTILIZATION/DISPOSAL OPTIONS

CONTACT POINTS

Scott M. Klara
Sequestration Product Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Karen Cohen
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-6667
karen.cohen@netl.doe.gov

Richard Doctor
Argonne National Laboratory (ANL)
9700 South Cass Avenue
Argonne, IL 60439
630-252-5913
rdoctor@anl.gov

CUSTOMER SERVICE

800-553-7681

WEBSITE

www.netl.doe.gov

Background

Concerns over possible global climate changes due to increasing atmospheric concentrations of greenhouse gases, such as carbon dioxide, have led to a strong emphasis on the development of high-efficiency, coal-based energy systems, incorporating the recovery of CO_2 for sequestration or use. One approach is the use of oxygen fired combustion with flue gas recycle to maintain a normal temperature profile in the furnace. The product directly leaving the boiler then is a CO_2-rich stream that is ready for sequestration or use with only modest conditioning. Conditioning is required to dry the CO_2, remove oxygen to prevent corrosion in the pipeline, and possibly other contaminants and diluents such as nitrogen, SO_2 and NOx.

The U.S. Department of Energy is investigating the feasibility of retrofitting boilers using this concept as a strategy for CO_2 recovery from conventional pulverized coal plants. This approach was conceived nearly twenty years ago at Argonne National Laboratory (ANL) as a low-cost CO_2 source for enhanced oil recovery (EOR). A molar ratio of CO_2/O_2 of about 3 is necessary to preserve the heat transfer performance and gas path temperatures, allowing this system to be applied as a retrofit. ANL is studying all the engineering aspects of this system, including the effect of impurities, such as SO_2 and NOx, and CO_2 transportation, use, and options for long-term sequestration. If the flue gas can be recycled before SO_2 scrubbing, significant cost savings are possible.

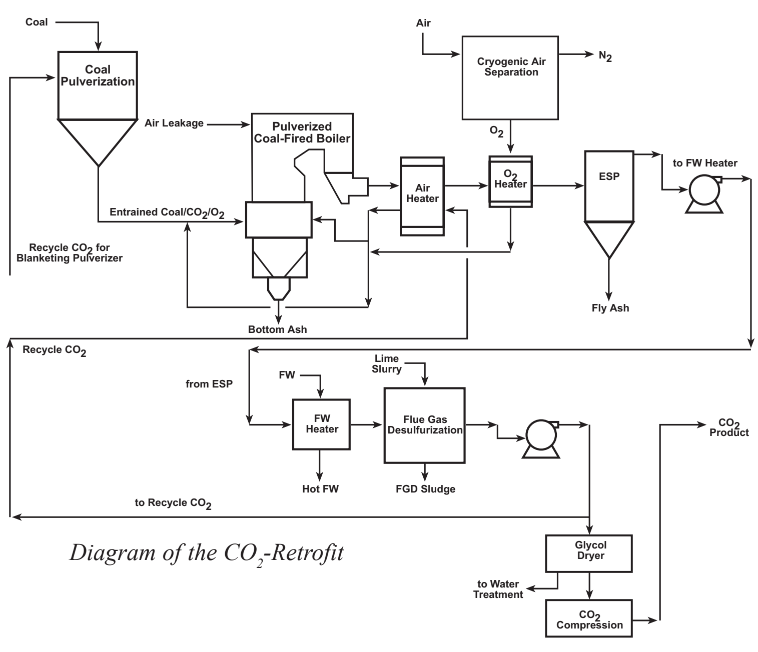


Diagram of the CO_2-Retrofit

CO_2 Capture for PC-Boiler Using Flue-Gas Recirculation: Evaluation of CO_2 Capture/Utilization/Disposal Options

PRIMARY PARTNER

Argonne National Laboratory

DOE FUNDING PROFILE

DOE	$ 569,000
Non-DOE	$ 0

COST

DOE	$ 569,000

This project will provide the power industry with a low-cost retrofit system that could remain in service during future upgrades at the power plant. The captured CO_2 can be used for EOR or sequestered. Overall, this project addresses both design and full energy-cycle issues pertaining to our current coal-fired power plants.

Primary Project Goal

The goal of the project is to conduct comparative engineering assessments of technologies for the recovery, transportation, and utilization/disposal of CO_2 produced in high-efficiency, coal-based, energy systems. Coordinated evaluations will address CO_2 transportation, CO_2 use, and options for long-term sequestration. Commercially available CO_2 capture technologies will provide performance and economic baselines for comparing innovative CO_2 recovery technologies across the full energy-cycle.

Objectives

The major objective is to develop engineering evaluations for the recovery of CO_2 from pulverized-coal-fired power plants retrofitted for flue-gas recirculation and to reconcile and extend these studies across the full energy-cycle.

Another object is to extend this analysis to identify plants that may be retrofit candidates considering the effects of different coals and the accessibility of a sequestration zone.

Accomplishments

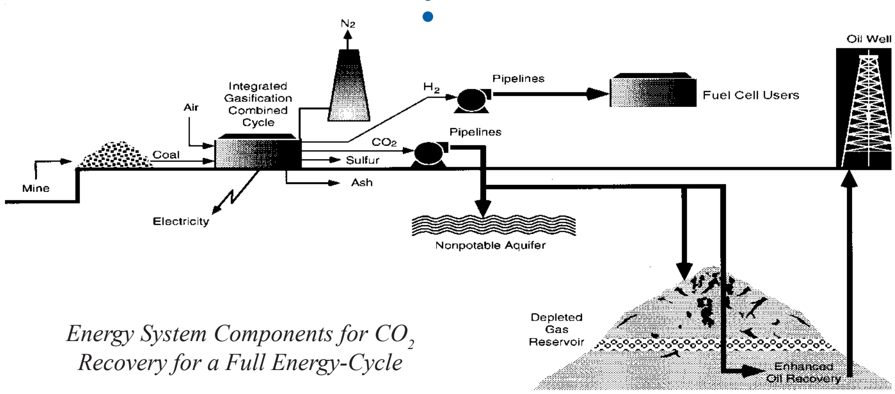
An oxygen-blown KRW coal-gasification plant producing hydrogen, electricity, and supercritical CO_2 was studied in a full-energy cycle analysis extending from the coal mine to the final destination of the gaseous product streams to establish energy and cost comparisons against a Vision 21 facility.

A full energy-cycle was evaluated based on simulation of an O_2 blown PC boiler with CO_2 recovery and flue-gas recircula-tion that includes details of the stream compositions for the whole system.

A transport-reservoir injection simulation that can handle noncondensable and contaminate gases was validated.

A study that shows the cost-effectiveness for flue gas recirculation vs. monoethano-lamine (MEA) scrubbing for CO_2 capture was completed.

It has been shown that CO_2 does not interfere with the scrubbing of SO_2 from a stream with a high concentration of CO_2.



Energy System Components for CO_2 Recovery for a Full Energy-Cycle

Benefits

Pulverized coal plants are the most common type of power plant; therefore, a system that can be retrofit to such boilers and enable CO_2 recovery will have broad applicability. Flue gas recirculation eliminates the need for N_2/CO_2 separation and sulfur separation, permitting more economical CO_2 recovery than competing amine systems. Technical and economic analyses will build on current accomplishments to develop a lower cost CO_2 capture technology.

Proj203.pmd

PROJECT facts

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

Sequestration

07/2004

GREENHOUSE GAS EMISSIONS CONTROL BY OXYGEN FIRING IN CIRCULATING FLUIDIZED BED BOILERS

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Timothy Fout
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880
304-285-1341
Timothy.Fout@netl.doe.gov

Nsakala ya Nsakala
ALSTOM Power, Inc.
2000 Day Hill Rd.
Windsor, CT 06095
860-285-2018
Fax: 860-285-2018
nsakala.y.nsakala@power.alstom.com

Background

The object of oxygen-fired combustion is to burn the fuel in enriched air or pure oxygen to produce a concentrated stream of CO_2. Oxygen fired combustion presents significant challenges, but also provides a high potential for technology breakthroughs and a step-change reduction in CO_2 separation and capture costs. Barriers and issues include: 1) oxygen from cryogenic air separation is expensive, and oxygen combustion consumes several times more oxygen than gasification; 2) combustion of fuels in pure oxygen occurs at temperatures too high for existing boiler or turbine materials, while CO_2 recycle to control temperature increases the parasitic power load.

Development and costing of an optimized oxygen fired combustion scheme requires an engineering study to identify and resolve the technical issues related to application of oxygen firing with flue gas recycle to a boiler and its associated process heaters. Alstom Power has proposed a two-case approach in which evaluations would analyze both fossil fuel (coal and petroleum coke) based and biomass based circulating fluidized bed (CFB) for power production. The first case will be to identify and analyze normal baseline conditions for CFB combustion with air firing, both without CO_2 capture and with a novel high-temperature CO_2 capture and sorbent regeneration process. Then, CFB-based concepts, employing an oxygen/flue gas mixture as the oxidizing agent, will be studied to determine what operating conditions and gas clean-up processes are most economical. The CO_2 concentration in the flue gas can be greatly increased by using oxygen instead of air for combustion.

In the second case, indirect combustion of coal, also known as chemical looping, will be evaluated. In chemical looping, synthesis gas (a mixture of CO and H_2) reduces a solid transition metal oxide to a lower oxidation state in a fluidized bed reactor with the production of water and CO_2. The off gas stream is cooled to condense water and produce a pure CO_2 stream for sequestration. The reduced metal containing solid is transferred to a second fluidized bed reactor, where it is reoxidized with air. This exothermic reaction heats the oxygen-depleted air, which is sent to power production.

Comparisons will be made with the Integrated Gasification Combined Cycle (IGCC) cases that have already been evaluated by Parsons Energy and Chemical Group. In this way, important features that can improve plant operations by utilizing oxygen firing will be explored, identified, and included in plant designs.

Greenhouse Gas Emissions Control by Oxygen Firing in Circulating Fluidized Bed Boilers

PRIMARY PARTNER

Alstom Power Inc.
ABB Lummus Global, Inc.
Praxair, Inc.
Parsons Energy and Chemical Group

COST

Total Project Value:	$2,537,491
DOE:	$2,029,992
Non-DOE Share:	$ 507,499

CUSTOMER SERVICE

800-553-7681

WEBSITE

www.netl.doe.gov

Primary Project Goal

The overall project goal is to conduct economic evaluations of the recovery of carbon dioxide using a newly constructed CFB combustor while burning coal, petroleum coke, or biomass fuel with a mixture of oxygen and recycled flue gas, instead of air.

Objectives

- The Phase I objective is to determine which of the new concepts in a CFB are technically feasible and have the potential of reducing the target cost of carbon avoided.
- Petroleum coke and coal samples will be combustion tested in a 4-inch Fluid Bed Combustion reactor to determine their gaseous (NO_x, SO_2, CO) and unburned carbon emissions and ash agglomeration/sintering potentials during combustion in oxygen-rich environments.
- The Phase II objective is to generate a refined technical and economic evaluation of the most promising concept for reducing CO_2 mitigation costs (based on recommendations from Phase I), based on data from proof-of-concept testing of the most promising concept.

Accomplishments

Phase I has been completed. The performance analysis of the base case (Air-Fired) CFB has been conducted. Key results included plant-efficiency, equipment costs, cost of electricity, and CO_2 mitigation costs. Work was completed on design/performance analyses of:

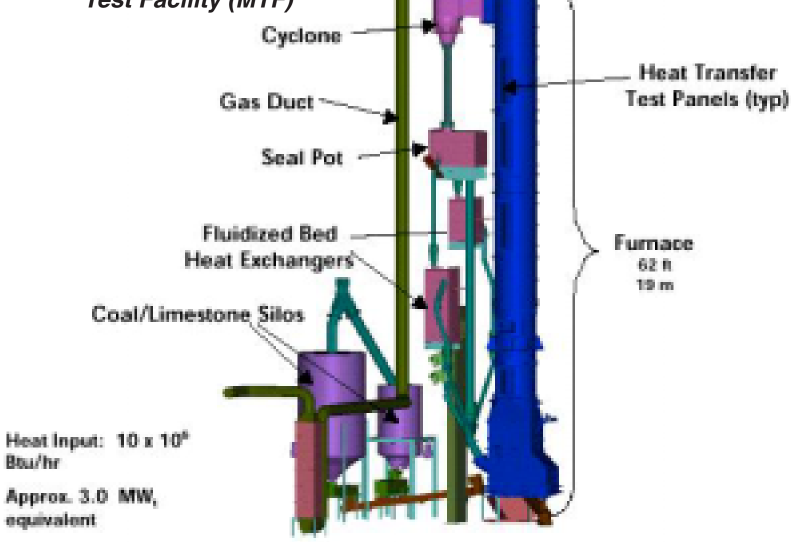
- Three advanced O_2-fired CFB concepts
- One high temperature carbonate regeneration process
- One chemical looping concept
- Two IGCC cases (one base case without CO_2 capture and one with a water-gas shift reactor to capture CO_2).

Phase II pilot testing has been initiated. The test facility is undergoing modifications to perform the planned pilot tests.

Benefits

The results from this project will provide the power industry with concrete data concerning greenhouse gas emissions control by oxygen firing in circulating fluidized bed boilers. The comparison of the several different technologies will target the most economical gas clean-up configuration.

ALSTOM's Multi-Use Test Facility (MTF)



Proj201.pmd

PROJECT facts

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

Sequestration

07/2004

NETL

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

David Lang
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4881
David.Lang@netl.doe.gov

Gary T. Rochelle
University of Texas
Principle Investigator
P.O. Box 7726
Austin, TX 78713
512-471-7230

Carbon Dioxide Capture by Absorption with Potassium Carbonate

Background

Alkanolamine solvents and solvent blends have been developed as commercially viable options for the absorption of CO_2 from waste gases, natural gas, and H_2 streams. Both primary and secondary amines are used in CO_2 capture processes. Monoethanolamine (MEA), considered to be the state-of-the-art technology, gives fast rates of absorption and favorable equilibrium characteristics. Secondary amines, such as diethanolamine (DEA), also exhibit favorable absorption characteristics.

Although alkanolamines have proven to be commercially successful, there is still room for process improvement. The promotion of potassium carbonate (K_2CO_3) with amines appears to be a particularly effective way to improve overall solvent performance. K_2CO_3 in solution with catalytic amounts of piperazine (PZ) has been shown to exhibit a fast absorption rate, comparable to 30 wt% MEA. Equilibrium characteristics are also favorable, and the heat of absorption (10-15 kcal/mol CO_2) is significantly lower than that for aqueous amine systems. Studies also indicate that PZ has a significant rate of reaction advantage over other amines as additives.

The Chemical Engineering Department at the University of Texas at Austin will develop a K_2CO_3/PZ solvent system that can captures more CO_2 while using 25-50% less energy than conventional MEA scrubbing. Using less energy will increase net electric power production from coal-fired plants when capturing and storing CO_2. By expanding on bench-scale modeling and pilot-scale experiments, the university will develop and validate a process model to optimize solvent rate, stripper pressure and other parameters. As gas/liquid contact and CO_2 mass transfer are enhanced, capital costs should be reduced.

Picture of the Pilot Plant

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

University of Texas at Austin

COST

Total Project Value:
$781,677

DOE/Non-DOE Share:
$515,519 / $266,158

The first task will consist of a rigorous modeling activity that will provide the basis for interpolating and extrapolating bench and pilot scale experimental results from previous and parallel bench scale work. The model will predict performance of absorption/stripping of CO_2 with aqueous K_2CO_2 promoted by PZ. Modifications to the model inputs will be made based on results of the pilot plant work to be conducted as part of the second task.

Primary Project Goal

The primary goal of this work is to develop an improved process for CO_2 capture by alkanolamine absorption/stripping by demonstrating an alternative solvent, aqueous K_2CO_3 promoted by PZ. This will involve the development of a model to predict performance of absorption/stripping of CO_2 using the improved solvent and carrying out a pilot plant study to validate the process model.

Objectives

- To improve the process for CO_2 capture by developing aqueous K_2CO_3 promoted by PZ as an alternative solvent to MEA.
- To develop a system model based on data from bench-scale operations.
- To perform pilot-scale experiments to validate the process model and define the range of feasible process operations.
- To optimize process variables, such as operating temperature, solvent rate, stripper pressure, and other parameters.
- To quantify the effectiveness of the promoter.

Accomplishments

- The existing pilot plant facility has been upgraded with stainless steel piping and heat exchangers to provide a flexible absorption/stripping system with feed gas containing 3 to 12% carbon dioxide and a stripper that can operate over a wide range of pressure.
- Simple models have been developed to predict the absorber and stripper performance.
- A rigorous model has been developed to represent the thermodynamics of aqueous potassium carbonate promoted by piperazine. The heat of CO_2 absorption is predicted to be 25 to 50% less than in the baseline monoethanolamine solvent.

Benefits

The major benefit of this project would be decreasing the energy requirement for CO_2 capture from fuel gas or flue gas streams. Should CO_2 capture and sequestration become necessary, an improved capture process would significantly improve overall plant efficiency. The capital and operating costs for CO_2 capture could also be reduced.

Proj280.pmd

PROJECT facts

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

Sequestration

03/2004

An Integrated Modeling Framework for Carbon Management Technologies

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Sarah Forbes
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
Morgantown, WV 26501
304-285-4670
sarah.forbes@netl.doe.gov

Edward S. Rubin
Carnegie Mellon University
Pittsburgh, PA 15213
412-268-5897
rubin@cmu.edu

Background

The Carbon Sequestration Program of DOE's National Energy Technology Laboratory (NETL) has the goal of developing safe, lower-cost methods of carbon capture and sequestration as a potential future option for greenhouse gas mitigation. One element of this program involves the development of modeling and assessments tools to evaluate and compare the overall effectiveness, costs, and sequestration potential of alternative carbon management methods. Tools also are needed to help identify and prioritize the most promising R&D efforts. The project described here was among the first group of projects selected by DOE/NETL in July 2000 under the Carbon Sequestration Program initiative.

Primary Project Goal

The primary goal of this project is to support modeling and assessment activities by developing a systematic framework for characterizing the performance and cost of alternative carbon capture and sequestration technologies applicable to a broad range of electric power systems.

Objectives

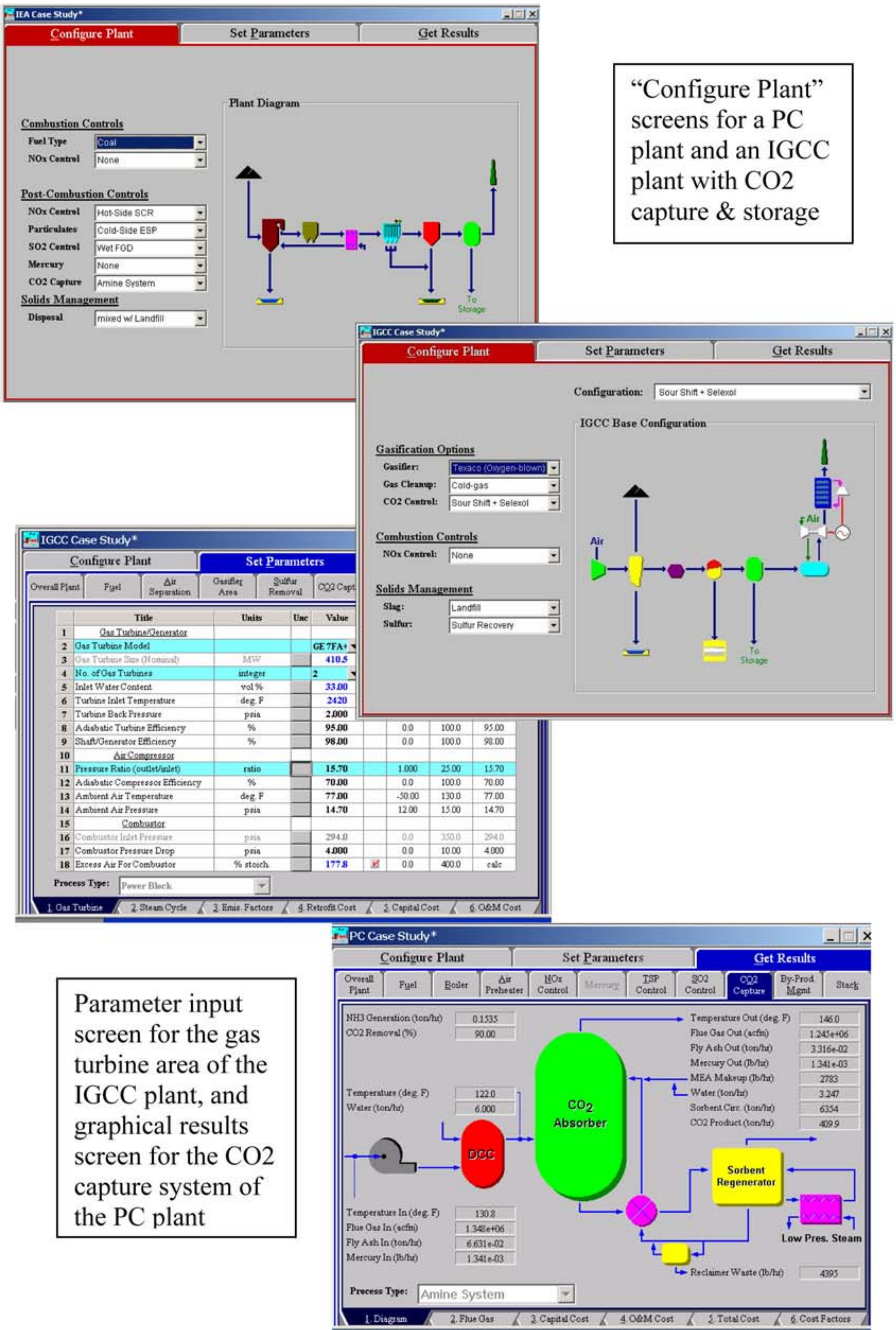
The product of this work is an easy-to-use, state-of-the-art computer model that allows different technology options for CO_2 capture and storage to be evaluated systematically at the level of an individual plant or facility. The model takes into account not only the avoided carbon emissions, but also the multi-pollutant impacts on criteria air pollutants, air toxics and solid wastes. Uncertainties and technological risks also can be explicitly characterized. The modeling framework includes combustion-based power plants using pulverized coal (PC), natural gas-fired combined cycle plants (NGCC), and integrated gasification combined cycle (IGCC) plants using coal or other solid fuels. The model can be employed to identify the most cost-effective carbon capture and storage options for a particular application. It also can be used to quantify the benefits of technology R&D, and to identify advanced technology options having the highest potential payoffs.

Accomplishments

The result of this effort is a computer model called IECM-CS (Integrated Environmental Control Model—Carbon Sequestration Version). This project extends earlier work on emission control options for criteria air pollutants and air toxics. The IECM-CS now includes a set of “baseline” technologies representing currently available CO_2 capture and storage (CCS) systems that could be employed at new or existing fossil-fuel power plants, including PC, NGCC and IGCC units. The cost and performance of CO_2 capture systems are evaluated in the context of multi-pollutant control systems for major air pollutants such as SO_2, NO_x, particulates and Hg. The CCS options include pipeline transport to alternative geologic or other CO_2 storage sites, including EOR and ECBM applications.

The modeling framework is being further extended to include a set of advanced technology options for both combustion-based and gasification-based systems, including oxyfuel combustion and advanced IGCC plant designs. More detailed models of CO_2 transport and storage options also are under development. The IECM has been used for preliminary evaluations of the cost of CCS using current technology for both new and retrofit applications. It also has been used to assess the uncertainty and variability surrounding cost and performance estimates for CO_2 capture and storage, and the magnitude of potential cost reductions from new or improved capture technology.

Examples of IECM-CS Graphical User Interface Screens



"Configure Plant" screens for a PC plant and an IGCC plant with CO2 capture & storage

Parameter input screen for the gas turbine area of the IGCC plant, and graphical results screen for the CO2 capture system of the PC plant

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

Carnegie Mellon University

COST

Total Cost:
$ 896,400

DOE/Non-DOE Share:
$ 717,200/ $ 179,200

Duration of Contract:
36 months

Benefits

Several important benefits accrue from this project:

- The IECM-CS provides users with a powerful and flexible tool for analyzing the performance and cost of alternative carbon capture technologies for a particular power plant application. In a carbon-constrained world, this will allow companies to avoid the need and high cost of engaging other firms to perform preliminary engineering analyses of CCS options.

- The IECM-CS is publicly available and free of charge to users. Earlier versions of the IECM have been widely distributed and used by a broad range of individuals and organizations with interests in electric power systems and environmental control options.

- The model runs quickly and easily on a modern laptop or desktop computer. Thus, it allows users to perform a wide range of analyses without costly setup time or waiting for results.

- The model is supported by a team of experienced researchers. It is fully documented and updated periodically to reflect ongoing technological developments.

- The "systems" framework embodied in the IECM allows carbon capture options to be evaluated in the context of other power plant emission control requirements. Such interactions can be extremely important, but are often overlooked in studies that focus only on one technology.

PROJECT facts

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

Sequestration

07/2004

Conceptual Design of Oxygen-Based PC Boiler

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Timothy Fout
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-1341
timothy.fout@netl.doe.gov

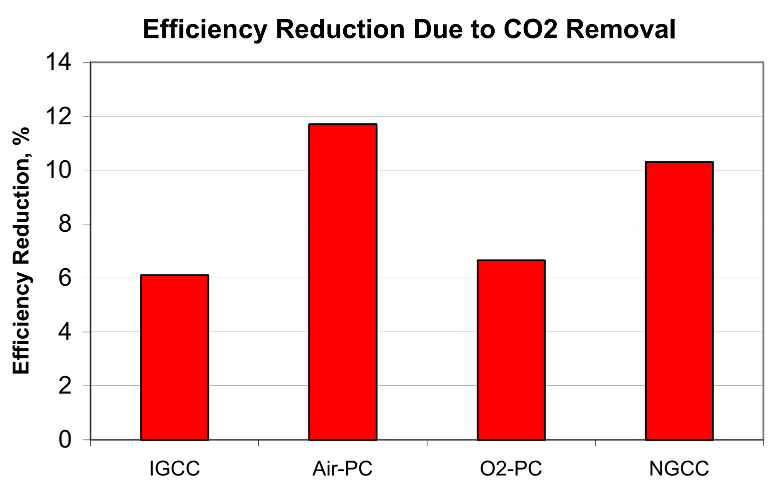
Andrew Seltzer
Foster Wheeler Development Corporation
12 Peachtree Hill Road
Livingston, NJ 07039
973-535-2542
andrew_seltzer@fwc.com

Background

Because of growing concern that a link exists between global climatic change and emission of greenhouse gases, such as CO_2, it is prudent to develop new coal combustion technologies to meet future emissions standards, should it become necessary to limit CO_2 emissions to the atmosphere. New technology is needed to ensure that the U.S. can continue to generate power from its abundant domestic coal resources. This project will design an optimized combustion furnace to produce a low-cost, high-efficiency power plant that supports the U.S. Department of Energy's (DOE) goal of developing advanced combustion systems that have the potential to control CO_2 through an integrated power system that produces a concentrated CO_2 stream for subsequent use or sequestration. Specifically, this work will evaluate the technical viability and economic competitiveness of an oxygen-enriched, pulverized coal (PC) fired boiler system with CO_2 sequestration. When oxygen is used in place of air as the combustion medium, the flue gas has a high concentration of CO_2, making recovery of CO_2 for sequestration much more economic.

Primary Project Goal

The primary goal of this project is to develop a conceptual PC-fired power plant, using oxygen as the combustion medium to facilitate the capture of CO_2 for subsequent sequestration.



CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

Foster Wheeler
Development Corporation

COST

Total Project Value
$406,482

DOE/Non-DOE Share
$325,186/$81,296

Objectives

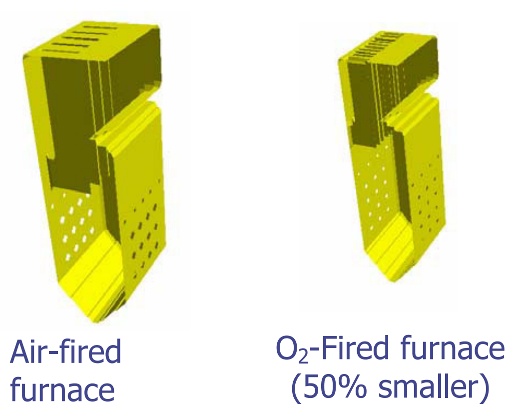
- Conduct a literature review to evaluate previous work in this area.
- Develop process modeling simulations for a conceptual design for an oxygen-enriched, PC-fired boiler with CO_2 capture.
- Develop a conceptual power plant design.
- Estimate costs for this conceptual power plant.
- Predict power plant performance and emissions and compare the overall cost of electricity of the conceptual power plant to a conventional PC-fired power plant (460 MWe subcritical, natural circulation boiler firing high-volatile bituminous coal to produce 2,400 psig steam at 1,050ºF and reheat steam at 1,050ºF).

Accomplishments

The entire cycle has been modeled in Aspen-Plus, including mills, air heater, furnace, heat recovery banks, feed water heaters, and steam turbines. Parametric runs have been made to evaluate the effect of operating variables on furnace performance. These studies have led to several conclusions. A higher flame temperature results in a more compact furnace and less gas recycle (limited by maximum furnace wall temperature) and to a higher cycle efficiency due to greater boiler efficiency. Estimates indicate that the parasitic power requirement for CO_2 capture is considerably lower than for a conventional plant and is comparable to that for an integrated gasification combined cycle (IGCC) system. Similarly, efficiency loss due to CO_2 capture is lower than for a conventional plant and comparable to an IGCC system.

Benefits

This project is evaluating a potential new power generating technology which could have the same efficiency and CO_2 sequestration potential as IGCC in a simpler facility. A substantially reduced furnace size leads to cost benefits, and a simple plant design means high reliability. The new plant uses proven steam plant technology. New air separation techniques could significantly improve economics.



Spatial comparison of an air-fired furnace versus an oxygen-fired furnace.

Proj303.pmd

Conceptual Design of Optimized Fossil Energy Systems with Capture and Sequestration of CO_2

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Jose Figueroa
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4966
jose.figueroa@netl.doe.gov

Joan M. Ogden
Princeton Environmental Institute
27 Guyot Hall
Princeton University
Princeton, NJ 08544
ogden@princeton.edu

Background

There is growing concern over the effect of greenhouse gas emissions on global warming. Considerable effort is being expended on developing technology for the recovery and sequestration of CO_2 from point sources, such as power plants. However, these approaches will not work for diffuse sources, such as motor vehicles. To reduce emissions from this source, a new concept is required. The idea generating the most interest is that of a hydrogen-based economy. Since H_2 produces only water vapor when burned, using H_2 to fuel motor vehicles would significantly reduce CO_2 emissions.

This project will develop analytic and simulation tools to better understand system design issues and economics for a large scale fossil energy system with CO_2 sequestration, including a central fossil energy complex with coproduction of H_2 and electricity and CO_2 capture, a H_2 energy pipeline distribution infrastructure serving users (vehicles, etc.), and a CO_2 disposal infrastructure (CO_2 pipelines and sequestration sites). Possible transition strategies from today's energy system to one based on fossil-derived H_2 and electricity with CO_2 sequestration will also be examined.

This study will consider fossil energy complexes producing both H_2 and electricity, from either natural gas or coal, with sequestration of CO_2 in geological formations, such as deep saline aquifers. After the cost and performance characteristics of the system components (fossil energy complex, H_2 pipelines and refueling stations, CO_2 pipelines and sequestration sites, and H_2 energy demand centers) have been determined, the design of the entire system will be studied as a problem of cost minimization. Cost minimization has two parts: implementation of technical and economic models for each component in the system and development of optimization algorithms to size components and connect them via pipelines into the lowest cost network serving a particular energy demand. A possible site for a specific case study is the Midwestern United States, where substantial coal conversion capacity is presently in place, coal resources are plentiful, and potential sequestration sites in deep saline aquifers are widespread.

This project is utilizing data and component models of fossil energy complexes with H_2 production and CO_2 sequestration already developed or being developed as part of the ongoing Carbon Mitigation Initiative, a joint project of Princeton, BP, and Ford, as well as other models being adapted from previous studies.

Primary Project Goal

The primary objective of this study is to better understand system design issues and economics for a large-scale fossil energy system coproducing H_2 and electricity with CO_2 sequestration. A second objective is to examine possible transition strategies from today's energy system toward one based on fossil-fuel derived H_2 and electricity with CO_2 sequestration.

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

Princeton University

COST

Total Project Value
$252,956

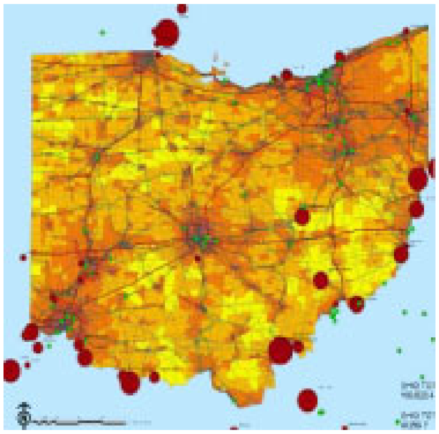
DOE/Non-DOE Share
$202,365/$50,591

Objectives

- To develop new analytic and simulation tools to model the design and evolution of fossil energy systems with CO_2 sequestration.
- To apply these simulation tools to carry out a geographically specific case study of development of a fossil-fuel based H_2 system with CO_2 sequestration.
- To minimize the cost of CO_2 disposal and delivered H_2 by cooptimizing the design of the fossil energy conversion facility and the CO_2 and H_2 pipeline networks.
- To examine possible transition strategies to a future energy system based on production of H_2 and electricity from fossil fuels with capture and sequestration of CO_2 in geologic formations, such as deep saline aquifers.
- To develop a concept for two new pipeline infrastructures, one for H_2 distribution and one for CO_2 disposal.
- To examine how H_2 infrastructure design and cost depend on geography and environment.

Accomplishments

As a first step, a simple analytical model has been developed that links the components of the system. This model considers a single fossil energy complex connected to a single CO_2 sequestration site and a single H_2 demand center. Cost functions have been developed for CO_2 disposal cost and delivered H_2 cost with explicit dependence on input parameters (size of demand, fossil energy complex process design, aquifer physical characteristics, distances, pressures, etc.). To better visualize results, a geographic information system (GIS) format will be used to show the location of H_2 demand, fossil energy complexes, coal resources, existing infrastructure (including rights of way), potential CO_2 sequestration sites, and optimal CO_2 and H_2 pipeline networks. A survey of relevant GIS data sets has been conducted, and work has begun on building a database.



GIS Data Base for Ohio, showing hydrogen demand density; coal fired power plants (red circles); limited access roads and railroads; electric transmission lines, CNG stations

Benefits

If the U.S. is to make significant progress on decreasing greenhouse gas emissions while simultaneously remaining economically competitive, new approaches to energy management and supply will be needed. Since fossil fuels, particularly coal, are our lowest cost energy resource, we will have to continue using them for some time into the future. This study will investigate ways to do this in an economically and environmentally acceptable way. One option, production of H_2 from fossil fuels with capture and sequestration of CO_2, offers a route toward near zero emissions in the production and use of fuels, and we need to have a better understanding of this option. This understanding, generated by this project, will be very valuable as we make future energy decisions.

Proj284.pmd

SORBENT DEVELOPMENT FOR CARBON DIOXIDE SEPARATION AND REMOVAL — PRESSURE SWING ADSORPTION & TEMPERATURE SWING ADSORPTION

PRIMARY PARTNER

National Energy Technology Laboratory

Carnegie Mellon University

Süd Chemie

DOE FUNDING PROFILE

Prior FY's	$ 400,000
FY2002	$ 400,000
Future FY	TBA

TOTAL ESTIMATED COST

DOE	$ 800,000

CUSTOMER SERVICE

800-553-7681

WEBSITE

www.netl.doe.gov

Background

Selective separation of CO_2 can be achieved by the preferential adsorption of the gas on high-surface area solids. Conventional physical adsorption systems are operated in pressure swing adsorption (PSA) and temperature swing adsorption (TSA) modes. In PSA, the gas is absorbed at a higher pressure. Then pressure is reduced to desorb the gas. In TSA, the gas is absorbed at a lower temperature. Then, the temperature is raised to desorb the gas. PSA and TSA are some of the potential techniques that could be applicable for removal of CO_2 from high-pressure gas streams, such as those encountered in Integrated Gasification Combined Cycles (IGCC).

Primary Project Goal

The object of this project is to develop regenerable sorbents that have high selectivity, high regenerability, and high adsorption capacity for CO_2 — properties critical for the success of the PSA/TSA process.

Objectives

- Develop a new class of more efficient sorbents that are operational at moderate or high temperatures.
- Complete a system analysis with moderate/high temperature PSA/TSA processes for separation of CO_2, along with molecular simulations of CO_2/surface interactions.

Sorbent Development for Carbon Dioxide Separation and Removal — Pressure Swing Adsorption & Temperature Swing Adsorption

CONTACT POINTS

Ranjani V. Siriwardane
Senior Scientist
Separations & Gasification Div.
National Energy Technology Laboratory
Office: B26-102
3610 Collins Ferry Road
Morgantown, WV 26505
304-285-4513
ranjani.siriwardane@netl.doe.gov

Curt White
Carbon Sequestration Focus Area Leader
National Energy Technology Laboratory
P.O. Box 10940
626 Cochrans Mill Road
Pittsburgh, PA 15236
412-386-5808
curt.white@netl.doe.gov

Accomplishments

Several zeolites from Süd Chemie were tested and have shown promising results.

Multi-cycle reactor tests showed that the highest adsorption capacity was observed when the major cation of the zeolites was sodium. A new class of sorbents (not zeolites) was prepared at NETL with excellent regenerability and high CO_2 adsorption capacity. Carnegie Mellon University (CMU) has initiated molecular simulations of CO_2 adsorption on zeolites in order to understand the selective adsorption process in zeolites. CMU is also conducting process simulation work on CO_2 Pressure Swing Adsorption to determine the optimal process. This process simulator, once validated, will be useful in developing sorption process performance estimates.

NETL developed sorbent

Benefits

The project shows considerable promise for developing a more energy efficient PSA process. This could also be applicable for removal of CO_2 from high-pressure gas streams, such as those encountered in Integrated Gasification Combined Cycle (IGCC) systems.

Proj190.pmd

*Factsheet Under Development

CO_2 Scrubbing with Regenerable Sorbent*
-NETL

Page left blank to accommodate 2-sided printing

***Factsheet Under Development**

Novel Amine-Enriched Sorbents*
-NETL

Page left blank to accommodate 2-sided printing

***Factsheet Under Development**

NO_2 & NOx and CO_2 Removal with Aqua Ammonia*
-NETL

Page left blank to accommodate 2-sided printing

R & D facts

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

Sequestration

02/2003

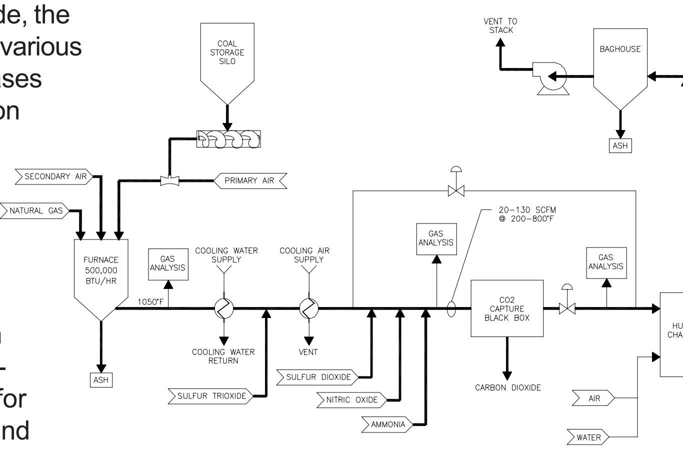
Modular Carbon Dioxide Capture Facility

Capabilities

Carbon Sequestration is rapidly becoming accepted as a viable option to reduce the amount of carbon dioxide (CO_2) emitted from large point sources, while continuing to use our Nation's fossil fuels to produce affordable, clean energy. As a major step in a carbon sequestration scenario (storage being the other), the capture or separation of carbon dioxide represents a significant cost and energy penalty in the overall sequestration process. To accelerate the development of low-cost capture and separation technologies, NETL is implementing the design and construction of a modular, flexible CO_2 capture test facility. The facility will be able to test new capture technologies on coal combustion flue gas and, additionally, on process gas from advanced fossil-fuel conversion systems, such as coal gasification. Ultimately, a database for a particular capture technology will provide experimental information from which further engineering scale-up decisions can be formulated.

In the flue gas mode, the Modular Carbon Dioxide Capture Facility (MCCF) will mimic coal-fired combustion processes that produce electricity. The combustor can be fired with natural gas, coal, or a combination of the two; coal-burning of approximately 40 pounds of pulverized coal per hour results in a flue gas (110-scfm) laden with various pollutants. The versatility of a "black-box" design will permit the incorporation of a particular capture/separation technology anywhere along the flue gas path. If regeneration of the capture medium is required as part of the capture/separation process, this step can be readily integrated into the system.

In a fuel gas mode, the MCCF will blend various high pressure gases (hydrogen, carbon monoxide, water, carbon dioxide, and minor components) to simulate the gas composition found in gasification processes, for example IGCC and Vision 21 plants.



CO_2 Capture Facility – Flue Gas

CONTACT POINTS

Henry Pennline
Chemical Engineer
412-386-6013
henry.pennline@netl.doe.gov

James Hoffman
Chemical Engineer
412-386-5740
james.hoffman@netl.doe.gov

Michael Nowak
Technology Transfer Officer
412-386-6020
michael.nowak@netl.doe.gov

National Energy Technology Laboratory

626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236-0940
412-386-4604 fax

4610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880
304-285-4469 fax

Modular Carbon Dioxide Capture Facility

Again, a versatile design will permit installation of a capture technology, possibly including regeneration, along the fuel gas flow network.

By providing a means to evaluate the most promising capture/separation CO_2-abatement processes, the MCCF will help DOE meet its goal of developing point source cleanup systems that are more efficient, cleaner, and less costly than the current established techniques proposed for implementation in today's power generation plants.

Opportunities

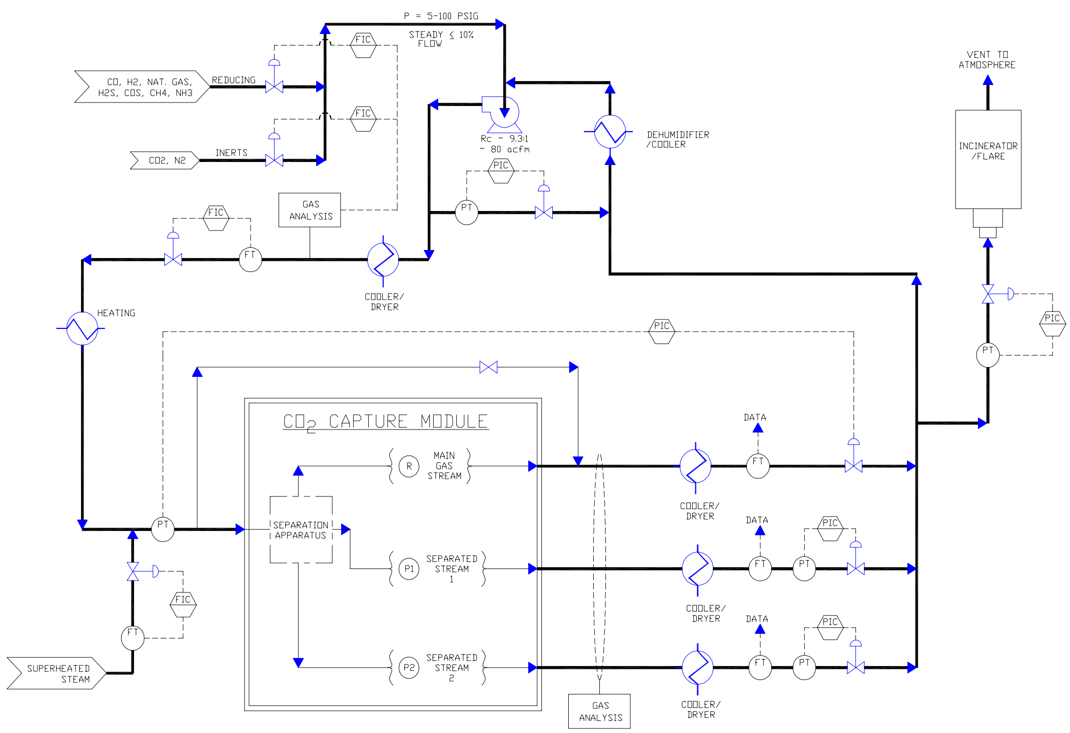
- The MCCF has evolved as a multipurpose, versatile research facility.
- Performance of a particular carbon dioxide-abatement process can be optimized in the MCCF to help achieve the extremely high emissions-control goals of the DOE Carbon Sequestration program. Operational performance standards for CO_2 capture will thus be established.
- The MCCF provides the ability to test capture and separation concepts on process streams that simulate advanced energy conversion systems.
- Side-by-side comparison of advanced capture and separation concepts can be conducted.
- The MCCF can be used to investigate the impact of gaseous components (SO_2, NO_x, H_2S, particulates, and/or air toxics emissions) and other parameters on the particular technology.
- The MCCF offers industry and other sequestration stakeholders the opportunity to further develop CO_2 capture/separation technologies through cooperative ventures with the government (NETL). Collaborations with CO_2 capture technology developers will be sought.

CUSTOMER SERVICE

800-553-7681

WEBSITE

www.netl.doe.gov/products/r&d



R&D034.pmd

PROJECT facts

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

Sequestration

12/2004

Combined Power Generation and Carbon Sequestration Using a Direct FuelCell®

Background

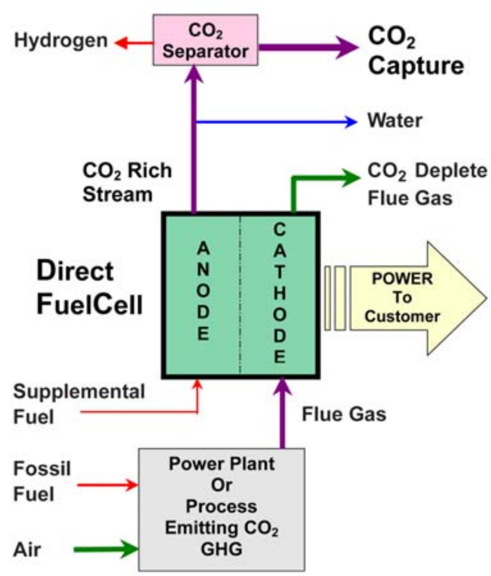
This project is responsive to the growing concern over global warming as a result of carbon dioxide emissions into the atmosphere from fossil fuel burning power plants and other industrial sources. FuelCell Energy (FCE) has developed a novel concept for the separation, capture, and potential sequestration of CO_2 emissions through the use of Direct FuelCell (DFC®) technology while concurrently generating power at high efficiency. The mitigation of the greenhouse effect through CO_2 sequestration is a new and unique application for DFC.

In the DFC, CO_2 is transferred from the cathode to the anode of the fuel cell resulting in a CO_2 rich exhaust stream, which can be sequestered. Key reactions are:

Anode: $H_2 + CO_3^{-2} \rightarrow H_2O + CO_2 + 2e^-$

Cathode: $\frac{1}{2} O_2 + CO_2 + 2e^- \rightarrow CO_3^{-2}$

Internal reforming of a hydrocarbon, such as natural gas, provides the hydrogen for the anode reaction. During normal fuel cell operation, some of the CO_2 from the anode exhaust is recycled to the cathode to form CO_3^{-2} ions that carry the current through the cell. In the concept of this project, the CO_2 is provided by passing flue gas over the cathode; and, as the fuel cell operates, the CO_2 in the flue gas is transferred from the cathode to the anode. The system will be studied to determine its effectiveness in capturing more than 90% of the carbon dioxide from the flue gas. The gain in electric power generated by the fuel cell is anticipated to result in a low net cost for carbon dioxide capture. Additionally, hydrogen from the anode exhaust may be recovered for sale or burned onsite to raise steam for a steam turbine generator.



CO_2 capturing system concept utilizing Direct FuelCell

CONTACTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

David A. Lang
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4881
david.lang@netl.doe.gov

Hossein Ghezel-Ayagh
FuelCell Energy, Inc.
3 Great Pasture Road
Danbury, CT 06813
203-825-6048
hghezel@fce.com

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

FuelCell Energy, Inc.

COST

Total Project Value
$171,222

DOE/Non-DOE Share
$136,978/$34,244

Benefits

One of the major problems in reducing CO_2 emissions from power plants is the high cost of recovering CO_2 from flue gas. This project is anticipated to result in a CO_2 separation and capture system based on an internally reformed DFC with potential for capturing at least 90% of GHG emissions generated by power plants and other industrial processes. The proposed system is targeted at no more than a 10% increase in the cost of electric power. If an inexpensive CO_2 capture system can be developed, then CO_2 sequestration could be practiced with minimal impact on the nation's economy.

This project will conduct the research and development essential for process optimization and cost estimation to ensure the successful implementation of the system. The design activities will be focused on integration of DFC-based CO_2 capture systems with coal-based power plants, which emit large amounts of greenhouse gases. The types of coal-fired power plants to be studied include pulverized coal (PC) fired, fluidized bed combustion, and integrated gasification combined cycle (IGCC). In parallel to the design activities, operation of a laboratory scale DFC will verify the benefits of the concept and provide input to the design activity. The anticipated result of this project is the development of a DFC-based CO_2 capture system that will increase the cost of electricity by less than ten percent.

FCE is a leading developer of DFC technology deployed for commercial power production applications. High volume manufacturing of fuel cells for power applications is projected to lower the cost of DFC based CO_2 sequestration systems. Considering that alternative technologies are energy intensive, expensive and/or complex, the efficient energy producing DFC carbon capture system is seen as a viable option for mitigating greenhouse gases from large point sources.

Primary Project Goal

The overall goal of this project is the development of a cost effective carbon separation and capture system utilizing a novel concept based on DFC technology.

Objectives

The objectives of this project are:

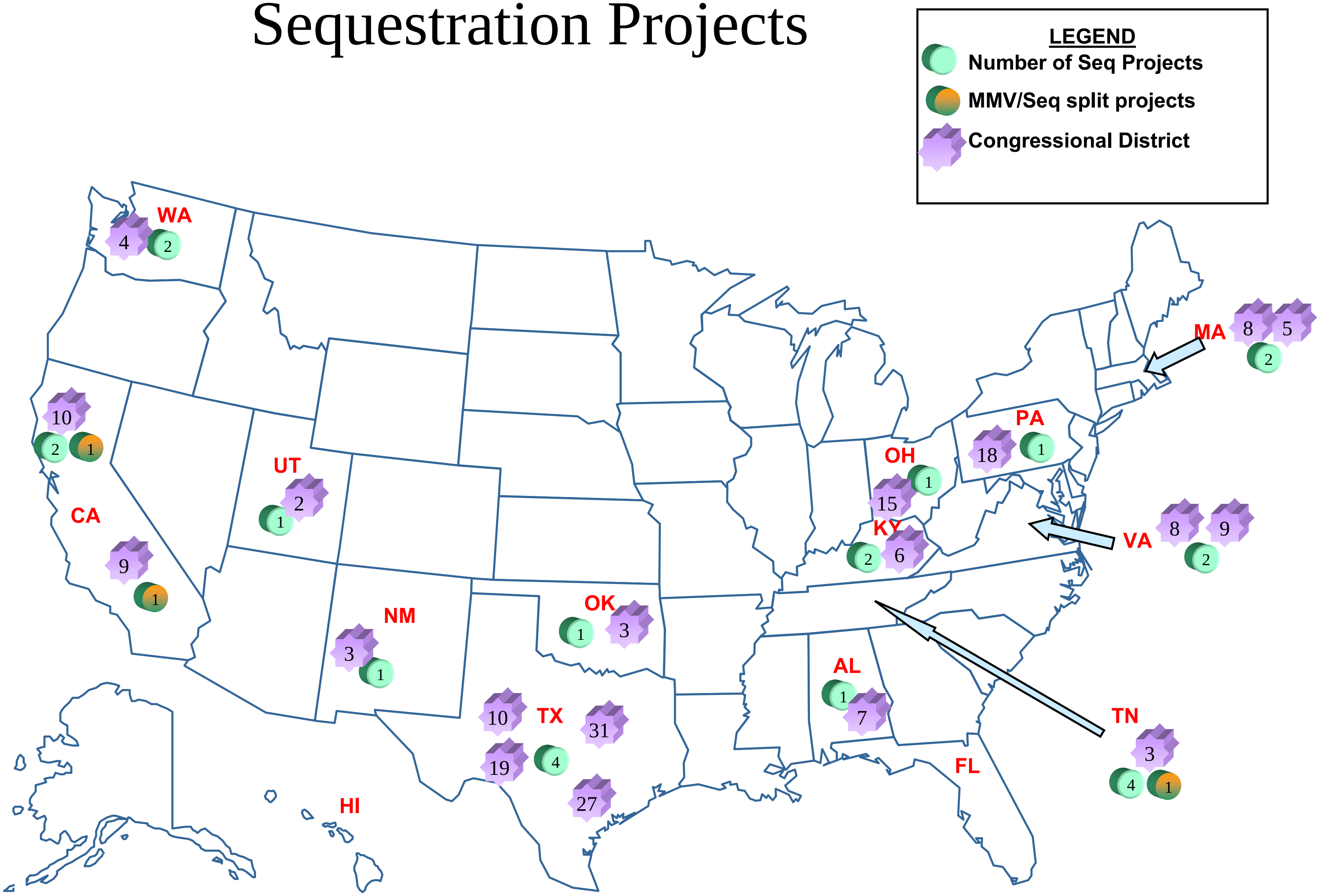
- To develop process design options for the integrated DFC-based CO_2 capture system to reduce GHG emissions from traditional coal-based plants, such as pulverized coal fired power plants, as well as advanced technologies, such as IGCC.
- To develop a database for various GHGs derived from coal fired power plants.
- To evaluate options for desulphurization of GHGs.
- To investigate techniques for the separation of CO_2 from the fuel cell anode exhaust.
- To perform detailed analysis using computer simulation of the DFC-based carbon capture system to verify the added benefits of simultaneous power generation and hydrogen by-product production.
- To determine the net cost of energy production after retrofitting a conventional power plant with DFC carbon capture.
- To experimentally validate simulation results and to refine equipment and cost models by conducting DFC tests in a lab-scale fuel cell using state-of-the-art fuel cell components.

Proj319.pmd

Sequestration

Page left blank to accommodate 2-sided printing

Sequestration Projects



Doesn't include NETL Projects

Page left blank to accommodate 2-sided printing

Project Title	Primary Contractor	Congressional District
Unmineable Coalbeds & Enhancing Methane Production Sequestering Carbon Dioxide	Oklahoma State University/Penn State University	OK03
Geologic Screening Criteria for Sequestration of CO_2 in Coal: Quantifying Potential of the Black Warrior Coalbed Methane in Fairway, Alabama	Alabama Geologic Survey	AL07
Optimal Geological Environments for Carbon Dioxide Disposal in Saline Aquifers	University of Texas at Austin (BEG)	TX10
Maximizing Storage Rate and Capacity and Insuring the Environmental Integrity of Carbon Dioxide	Texas Tech University	TX19
Geologic Sequestration of CO_2 in Deep, Unmineable Coalbeds	Advanced Resources International/ BP Amoco	VA08
Enhanced Coalbed Methane Production and Sequestration of CO_2 in Unmineable Coal Seams	Consol	PA18
Analysis of Devonian Black Shale in Kentucky for Potential Carbon Dioxide Sequestration and Enhanced Natural Gas Production	University of Kentucky Research Foundation	KY06
CO_2 Sequestration Potential of Texas Low-Rank Coals	Texas Engineering Experiment Station	TX31
Reactive, Multi-phase Behavior of CO_2 in Saline Aquifers Beneath the Colorado Plateau	University of Utah	UT02
Experimental Evaluation of Chemical Sequestration of CO_2 in Deep Saline Formations	Batelle Columbus Laboratories	OH15
GEO-SEQ	LBNL	CA09
GEO-SEQ	LLNL	CA10
GEO-SEQ	ORNL	TN03
Effects of Temperature and Gas Mixing in Underground Coalbeds	Oak Ridge National Laboratory	TN03
Feasibility of Large-Scale CO_2 Ocean Sequestration	Monterey Bay Aquarium Research Institute	CA10
CO2 Sequestration in Basalt Formation	Pacific Northwest National Laboratory (PNNL)	WA04
International Collaboration on CO_2 Sequestration (CO_2 Ocean injection)	MIT	MA08
Laboratory Investigations in Support of Carbon Dioxide-Limestone Sequestration in the Ocean	University of Massachusetts	MA05
Enhancement of Terrestrial C Sinks Through Reclamation of Abandoned Mine Lands in the Appalachians	Stephen F. Austin State University	TX27

Restoring Sustainable Forests on Appalachian Mined Lands for Wood Products, Renewable Energy, Carbon Sequestration, and Other Ecosystem Services	Virginia Polytechnic Institute and State University	VA09
Carbon Sequestration on Surface Mine Lands	University of Kentucky	KY06
Carbon Capture and Water Emissions Treatment System (CCWESTRS) at Fossil Fueled Electric Generation	Tennessee Valley Authority	TN03
Exploratory Measurements of Hydrate and Gas Compositions	LLNL	CA10
Enhanced Practical Photosynthesis Carbon Sequestration	ORNL	TN03
Enhancing Carbon Sequestration and Reclamation of Degraded Lands with Fossil Fuel Comb. ByProduct	PNNL ORNL	WA04 TN03

(NETL projects not included)

Sequestration - *Geological*

Technology Target

- Depleted Oil & NG Reservoirs – Feasibility of CO_2 storage and enhanced gas recovery
- Deep Coal Seams – Field demos of max CO_2 storage in coal seams
- Saline Aquifers:
  - — CO_2/fluid interactive studies
  - — Database
  - — Field demos of aquifer storage

Deep coal seams
- Lab tests for reservoir modeling studies
- Effects on CO_2 on major coal types
- Site selection criteria

Saline Aquifers
- CO_2-fluid interactive studies Geochemical and flow models

Depleted oil & NG reservoirs
- Geochemical research
- Database on cap rock
- Modeling & testing for maximized storage of CO_2
- Erosion of cement and corrosion of steel and possible cross effects

Other Studies
- Modeling & Assessment
- Indoor Bioreactor
- Shale

Consol
- Sequestration of CO_2 in coal seams.
- Economics
- CO_2 injection into degassed unmineable coal seam

ARI
- Geologic sequestration of CO_2 in unmineable coal beds.
- Demonstrate N_2/CO_2 – ECBM and CO_2 seq. process.
- Develop matrix & simulation

Alabama Geo Survey
- Geologic screening criteria
- Potential of specific site, mapping, target areas and capacity

ORNL
- Effects of temperature and gas mixing in underground coal beds

Texas Engr. Exp
- Evaluate the feasibility, environmental and economic impacts of seq. CO_2 in Texas low-rank coal bed

NETL
- Physics and chemistry of coal seam sequestration and coal bed methane production

BP – INEL
- CBM potential CO_2 Capacity

Battelle Columbus Labs
- Conduct reservoir simulation in regional aquifier

University of Texas
- Development of expertise in design and performances assessment of CO_2 disposal facilities

University of Utah
- Multiphase behavior of CO_2 in saline aquifers

NETL
- Geology and reservoir simulation for brine field
- Investigation of gas/water/rock interaction and chemistry
- Activiation of carbonation minerals for CO_2 Seq

BP – UT
- CO_2 Movement and immobilization

GEO-SEQ (LLNL, LBNL, ORNL)
- Joint project between academia and industry
- Optimize models with economic benefits
- Improve capacity assessment.
- Field demonstration program

Univ. of Kentucky
- Investigate shale's ability to release CH_4 by CO_2 adsorption

ORNL – Practical photosynthesis conversion

NETL
- Geologic sequestration core flow lab

PNNL
- Sequestration in basalt-formations

BP – ARI
- CO_2 Reservoirs

Sequestration - *Terrestrial & Ocean*

Technology Target

- Assess domestic opportunities in mined-land reclamation
- Complete final testing in representative regional terrestrial ecosystems
- Demonstrate the multiple benefits associated with terrestrial sequestration

Terrestrial Outcomes

- Demonstrate the reforestrationn of surface mine lands with high value hardwoods
- Afforstation and reforestation/enhancement activities for tradable credits

Stephen F. Austin
- Enhancement of terrestrial sinks by optimizing silvicultural techniques
- Model the reforestation of abandoned mine lands in the Appalachian region for carbon sequestration and forest products

Virginia Tech
- Restoring sustainable forests on Appalachian mined lands for wood products, renewable energy, carbon sequestration, and other ecosystem services

University of Kentucky
- Carbon sequestration on surface mine lands
- Study both the effects of tree species and spoil type and handling on carbon sequestration

ORNL/PNNL
- Investigate the use of industrial byproducts as soil enhancers

TVA
- Use by-products from coal combustion to reclaim coal mined lands

Technology Target

- Identify and assess potential perturbations from ocean sequestration process
- Assurance of predictability of CO_2 fate in oceans sequestration

Ocean Outcomes
- Pathway viability and long-term sequestration stability
- Flow models
- Feasibility study of CO_2 storage as a hydrate pool in bottom of the ocean

MBARI
- Investigate the chemical, physical, and biological behavior of CO_2 hydrates in the deep ocean.

LLNL
- Synthesize well-characterized CO_2 hydrates for testing

MIT
- Develop instrumentation and potential experiments for the international project on CO_2 ocean sequestration

University of Mass
- Establish a database for the improvement of deep water ocean sequestration using a CO_2-H_2O limestone emulsion

NETL
- Hydrate formation, water tunnel flow properties, and deep ocean injection study

Sequestration Project Fact Sheet List

Project Title	Primary Contractor	Fact Sheet Listing
Unmineable Coalbeds & Enhancing Methane Production Sequestering Carbon Dioxide	Oklahoma State University/Penn State University	S-8
Geologic Screening Criteria for Sequestration of CO_2 in Coal: Quantifying Potential of the Black Warrior Coalbed Methane in Fairway, Alabama	Alabama Geologic Survey	S-10
Optimal Geological Environments for Carbon Dioxide Disposal in Saline Aquifers	University of Texas at Austin (BEG)	S-12
Maximizing Storage Rate and Capacity and Insuring the Environmental Integrity of Carbon Dioxide*	Texas Tech University	S-14
Geologic Sequestration of CO_2 in Deep, Unmineable Coalbeds	Advanced Resources International	S-16
Enhanced Coalbed Methane Production and Sequestration of CO_2 in Unmineable Coal Seams	Consol	S-18
Analysis of Devonian Black Shale in Kentucky for Potential Carbon Dioxide Sequestration and Enhanced Natural Gas Production	University of Kentucky Research Foundation	S-20
CO_2 Sequestration Potential of Texas Low-Rank Coals	Texas Engineering Experiment Station	S-22
Reactive, Multi-phase Behavior of CO_2 in Saline Aquifers Beneath the Colorado Plateau*	University of Utah	S-24
Experimental Evaluation of Chemical Sequestration of CO_2 in Deep Saline Formations (Storage of CO_2 in the Geologic Formations in the Ohio River Valley Region)	Batelle Columbus Laboratories	S-26
Geological Sequestration of CO_2 : GEO-SEQ	LBNL, LLNL, ORNL	S-28
Strategies for Controlling Coal Permeability in CO_2-Enhanced Coalbed Methane Recovery	Oak Ridge National Laboratory	S-30
Feasibility of Large-Scale CO_2 Ocean Sequestration	Monterey Bay Aquarium Research Institute	S-32
CO_2 Sequestration in Basalt Formations	Pacific Northwest National Laboratory (PNNL)	S-34
International Collaboration on CO_2 Sequestration	MIT	S-36
Laboratory Investigations in Support of Carbon Dioxide-Limestone Sequestration in the Ocean	University of Massachusetts	S-38
Enhancement of Terrestrial C Sinks Through Reclamation of Abandoned Mine Lands in the Appalachians	Stephen F. Austin State University	S-40
Restoring Sustainable Forests on Appalachian Mined Lands for Wood Products, Renewable Energy, Carbon Sequestration, and Other Ecosystem Services	Virginia Polytechnic Institute and State University	S-42
Carbon Sequestration on Surface Mine Lands	University of Kentucky	S-44

* Factsheet Under Development

(BP CCP and UCR projects not included)

* Factsheet Under Development

PROJECT **facts**

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

Sequestration

07/2004

UNMINABLE COALBEDS & ENHANCING METHANE PRODUCTION SEQUESTERING CARBON DIOXIDE

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Dawn Chapman
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-4133
dawn.chapman@netl.doe.gov

Khaled Gasem
Principal Investigator
Oklahoma State University
423 Engineering North
Stillwater, OK 74078
405-744-9498
gasem@che.okstate.edu

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

Background

One method for sequestering carbon dioxide (CO_2) is to store it in natural geological formations, such as unminable coal seems. Most of the gas present in coal seams is stored on the internal surfaces of the organic matter. Because of its large internal surface area, coal can store 6 to 7 times more gas than the equivalent volume of a conventional gas reservoir. Most coal seams contain methane, the gas content generally increases with coal rank, depth of the coalbed, and reservoir pressure. Unmineable coalbeds are attractive targets for sequestration of CO_2 because they have a large storage capacity and the sequestered CO_2 can enhance the recovery of natural gas by displacing the methane that is present in the coalbeds.

Oklahoma State University is leading an effort to investigate and test the ability of injected carbon dioxide to enhance coalbed methane production. The specific focus of this project is to investigate the competitive adsorption behavior of methane, CO_2, and nitrogen on a variety of coals. Measurements are focused on the adsorption of the pure gases, as well as mixtures. Data will be taken on coals of various physical properties at appropriate temperatures, pressures, and gas compositions to identify the coals and conditions for which the proposed sequestration applications are most attractive.

Mathematical models are being developed to describe accurately the observed adsorption behavior. The combined experimental and modeling results will be generalized to provide a sound basis for performing reservoir simulation studies. These studies will evaluate the potential for injecting CO_2 or flue gas into coalbeds to simultaneously sequester CO_2 and enhance coalbed methane production. Future computer simulations will assess the technical and economic feasibility of the proposed process for specific candidate injection sites.

Primary Project Goal

The overall goal of this project is to develop accurate prediction methods (models) for describing the adsorption behavior of gas mixtures on coal over a complete range of temperature, pressure, and coal types.

Accomplishments

Several types of coals were characterized by their ability to adsorb nitrogen, methane, and CO_2. The low pressure adsorption of CO_2 and methane was studied in a volumetric apparatus. Significant progress in improving the predictive capability of the models has been made. The research will eventually determine how much methane is displaced by a given amount of CO_2.

UNMINABLE COALBEDS & ENHANCING METHANE PRODUCTION SEQUESTERING CARBON DIOXIDE

PROJECT PARTNERS

Oklahoma State University

Penn State University

Geo-Environmental Engineering
State College, PA

COST

Total Project Value	$674,980
DOE	$624,078
Non-DOE Share	$ 56,125

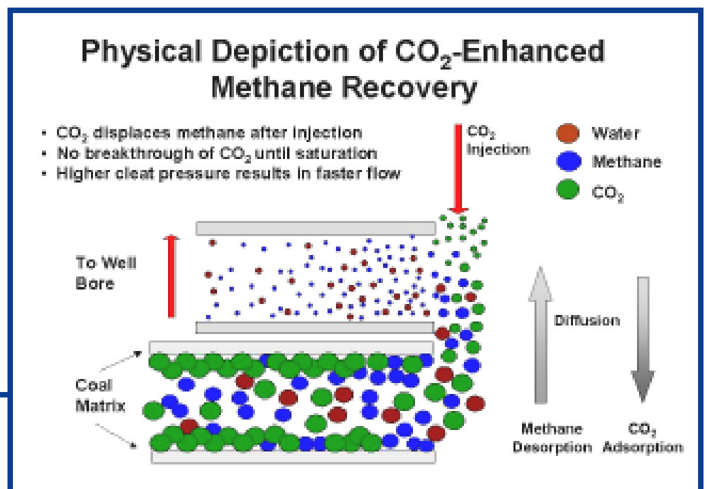
Objectives

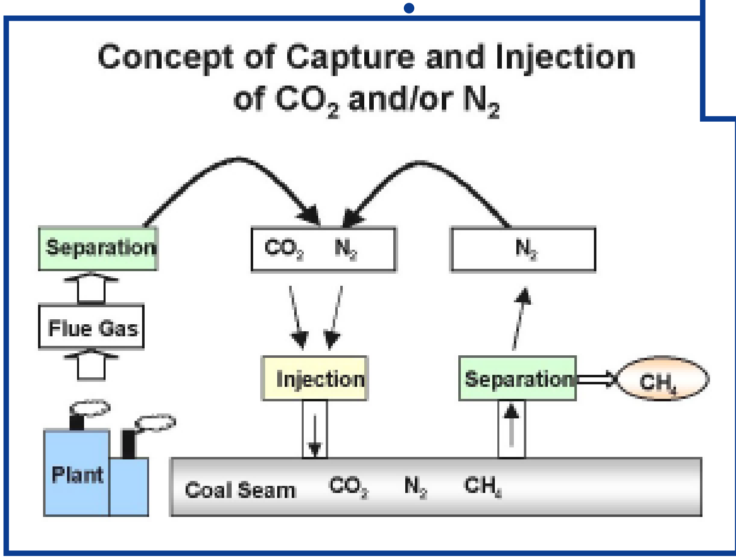
Proposed fourth year milestones

- Measure pure methane adsorption on three different coals and dry activated carbon.
- Develop and validate reliable, simple, analytic models capable of describing multi-layer adsorption.
- Further evaluate the vapor/liquid equilibrium analog model for possible prime candidate for use in CBM and CO_2 sequestering simulators.
- Study the adsorption of binary and ternary gas mixtures.

Benefits

This project will significantly enhance our understanding of multilayer adsorption of near critical and supercritical components on heterogeneous surfaces. The data and models developed will permit evaluation of the ability of coal to sequester CO_2, a major greenhouse gas, and simultaneously increase the supply of methane, a clean-burning energy source, and provide a sound basis for commercial implementation of this technology.





Proj212.pmd

PROJECT facts

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

11/2002

GEOLOGIC SCREENING CRITERIA FOR SEQUESTRATION OF CO_2 IN COAL: QUANTIFYING POTENTIAL OF THE BLACK WARRIOR COALBED METHANE FAIRWAY, ALABAMA

CONTACT POINTS

Scott M. Klara
Sequestration Product Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Charles Byrer
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-4547
charles.byrer@netl.doe.gov

Jack C. Pashin
Geological Survey of Alabama
P.O. Box 869999
Tuscaloosa, AL 35486
205-349-2852
jpashin@gsa.state.al.us

CUSTOMER SERVICE

800-553-7681

WEBSITE

www.netl.doe.gov

Background

The amount of carbon dioxide (CO_2) in the Earth's atmosphere has risen substantially since the start of the industrial age. This increase is attributed widely to the burning of fossil fuels, and if current trends in resource utilization continue, anthropogenic CO_2 emissions will triple during the 21st century. Among the principal ways CO_2 emissions from power plants can be addressed is to sequester this greenhouse gas in geologic formations. Within the geologic formations that can potentially store CO_2 are unminable coalbeds. Coalbeds are an especially attractive target because coal can store large quantities of gas. In this process of being adsorbed, the CO_2 displaces adsorbed methane. Thus, the sequestered CO_2 serves as a sweep gas to enhance recovery of coalbed methane.

The coalbed methane fairway of the Black Warrior basin is a logical location to develop screening criteria and procedures from numerous standpoints. According to the U.S. Environmental Protection Agency, Alabama ranks 9th nationally in CO_2 emission from power plants and two coal-fired power plants are within the coalbed methane fairway. More than 34 billion cubic meters of coalbed methane have been produced from the Black Warrior basin, which ranks second globally in coalbed methane production. Production is now leveling off, and enhanced coalbed methane recovery has the potential to offset impending decline and extend the life and geographic extent of the fairway far beyond current projections.

The Geological Survey of Alabama and its partners are conducting research to determine the amount of CO_2 that can be stored in the Black Warrior coal-bed methane region of Alabama.

Primary Project Goal

The primary goal of this project is to develop a screening model that is widely applicable, quantify CO_2 sequestration potential in Black Warrior CBM fairway, and apply screening modeling to identify favorable demonstration sites for CO_2 sequestration.

Geologic Screening Criteria for Sequestration of CO_2 in Coal: Quantifying Potential of the Black Warrior Coalbed Methane Fairway, Alabama

PROJECT PARTNERS

Geological Survey of Alabama
Tuscaloosa, Alabama

University of Alabama

Alabama Power Company
Bringingham, Alabama

Jim Walter Resources
Brookwood, Alabama

COST

Total Project Value:	$1,398,068
DOE	$ 789,565
Non-DOE Share:	$ 608,503

Objectives

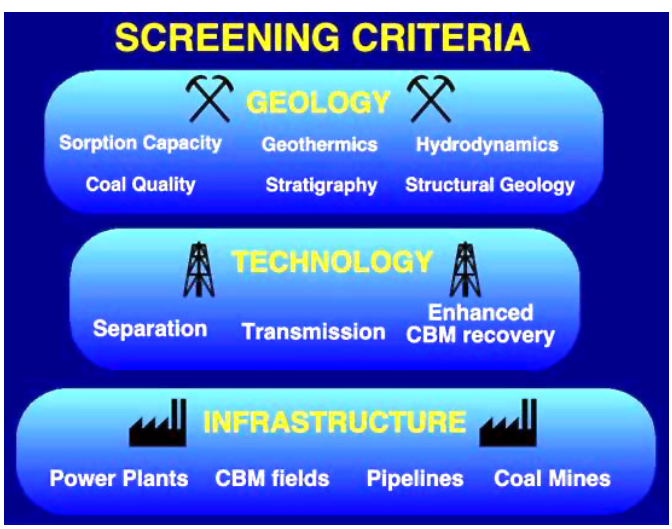
- Develop a geologic screening model for CO_2 sequestration sites that is widely applicable.
- Quantify the CO_2 sequestration potential of coals in the Black Warrior coalbed methane fairway, where two coal-fired power plants operate adjacent to a thriving coalbed methane industry.
- Apply the screening model to identify sites favorable for demonstration of enhanced coalbed methane recovery and mass sequestration of CO_2 emitted from coal-fired power plants in this basin of Alabama.

Accomplishments

Subsurface geological analyses have been performed on the Pottsville formation from the Black Warrior coalbed methane fairway. Hydrologic and geothermic data have been collected from more than 2,800 well logs and are being used to calculate reservoir pressure and geothermal gradient. Preliminary results confirm that coal can sorb significantly more carbon dioxide than methane while having relatively little capacity for nitrogen.

Benefits

The developed screening model will provide a widely applicable tool for evaluating potential geological sites for sequestration of CO_2. Ultimately, this project will result in sequestration of CO_2 and enhanced methane recovery from unmineable coalbeds. The technology results of the project will be transferred to the public, academia, and industry for application toward ultimate commercialization of sequestration technologies.



Variables that will be used to develop the screening model.

PROJECT facts

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

Sequestration

07/2004

Optimal Geological Environments for Carbon Dioxide Disposal in Saline Aquifers

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Dawn Chapman
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-4133
dawn.chapman@netl.doe.gov

Susan D. Hovorka
University of Texas at Austin
Bureau of Economic Geology
10100 Burnet Road, Bldg. 130
P.O. Box X
Austin, TX 78713
512-471-1534
susan.hovorka@beg.utexas.edu

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

Background

For CO_2 sequestration to be a successful component of the U.S. emissions reduction strategy, there will have to be a favorable intersection of a number of factors, such as the electricity market, fuel source, power plant design and operation, a suitable geologic sequestration site, and a pipeline right-of-way from the plant to the injection site. The concept of CO_2 sequestration in saline water-bearing formations (saline reservoirs), isolated at depths below potable aquifers, became of widespread interest in the early 1990's and is in the process of maturing from a general concept to one of the options used by oil and gas producers for isolating excess produced CO_2.

The University of Texas at Austin's Bureau of Economic Geology is developing criteria for characterizing optimal conditions and characteristics of saline aquifers that can be used for long-term storage of CO_2. Phase I of this project included identifying drilling locations for CO_2 injection wells and better defining saline-formation conditions suitable for CO_2 disposal and sequestration. During Phase II, saline water-bearing formations outside of oil and gas fields were investigated.

Recent research and development efforts have demonstrated the technical feasibility of the process, defined costs, and modeled technology needed to sequester CO_2 in saline aquifers. One of the simplifying assumptions used in previous modeling efforts is the effect of stratigraphic complexity on transport and trapping in saline aquifers. Phase III efforts will include field testing of a limited amount of CO_2 injected into a deep saline reservoir within the state of Texas to ascertain the interaction of the gas with the reservoir rock and to monitor the size and shape of the CO_2 plume within the reservoir.

Primary Project Goal

This project will develop and then apply criteria for characterizing saline aquifers for long term sequestration of CO_2. Current effort is directed at a field test of injecting a set amount of CO_2 into a deep saline reservoir and monitoring the interaction of the gas with the reservoir and the dispersion of the CO_2 with time.

Objectives

- Provide an appropriate target site for development of expertise in design and performance assessment of CO_2 disposal facilities.

Optimal Geological Environments for Carbon Dioxide Disposal in Saline Aquifers

PROJECT PARTNERS

University of Texas at Austin

Texas American Resources

B-P America

Schlumberger

Bureau of Economic Geology

Austin Texas

Lawrence Berkeley National Laboratory

Lawrence Livermore National Laboratory

Oak Ridge National Laboratory

COST

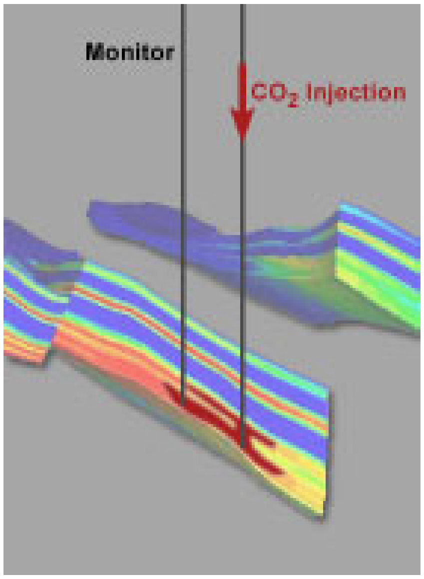
Total Project Value: $3,659,215
DOE $2,909,215
Non-DOE Share: $ 750,000

- Adequately characterize the field site for CO_2 disposal in a saline reservoir.
- Monitor behavior and migration of the CO_2.
- Develop conceptual models for CO_2 behavior.
- Provide information needed to characterize conditions affecting long-term containment of CO_2.

Accomplishments

Phase I of the project plotted the distribution and 1996 CO_2 output of power plants in the U.S. Geologic screening criteria for identifying suitable saline water-bearing formations for CO_2 sequestration were developed. Sufficient data was obtained about the properties of saline water-bearing formations in the pilot test areas to develop a prototype Geologic Information System (GIS) to demonstrate the effectiveness of this approach. The pilot study confirmed that information is available, either as basin-specific data sets or as products of geologic analogs and play analysis. Efforts were focused on reservoir and geological play analyses and geologic and hydrologic models to extrapolate from areas with abundant data into water-bearing formations with little data to identify those saline water-bearing formations that have the geological attributes conducive to successful pilot sequestration projects.

Phase II involved a regional inventory of geological environments of saline water-bearing formations for CO_2 disposal. This effort was focused on reservoir and geological play analyses and geologic and hydrologic models to extrapolate from areas of abundant data into poorly known water-bearing formations and identified those parts of saline water-bearing formations that have the geological attributes conducive to ensuring success of pilot sequestration projects. Phase III effort will highlight through field test, the degree to which CO_2 can be injected in saline aquifers.



Conceptual model of sequestering CO_2 in saline aquifers.

Benefits

This project will benefit industry by extending modeling and monitoring capabilities for sequestration into the geologic settings where very large-scale sequestration is feasible in the geographic areas where sequestration is needed. Non-productive brine bearing formations below and hydrologically separated from potable water have been widely recognized as having high potential for very long term (geologic time scale) sequestration of greenhouse gasses, and this site will provide a first field scale testing in this setting. It will also provide a regional U.S. data inventory of saline water-bearing formations.

Proj210.pmd

*Factsheet Under Development

Maximizing Storage Rate and Capacity and Insuring the Environmental Integrity of Carbon Dioxide*
-Texas Tech University

Page left blank to accommodate 2-sided printing

PROJECT facts

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

02/2005

Geologic Sequestration of CO_2 in Deep, Unmineable Coalbeds: A Fundamental Research and Field Demonstration Project ("Coal-Seq")

CONTACTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Scott R. Reeves
Executive Vice President
Advanced Resources International
9801 Westheimer, Suite 805
Houston, TX 77042
713-780-0815
sreeves@adv-res-hou.com

Charles Byrer
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-4547
charles.byrer@netl.doe.gov

Background

One approach to sequestering carbon dioxide (CO_2) is to inject it into deep, unminable coal seams. A particular advantage of coalseam sequestration is that coal seams can store several times more CO_2 than the equivalent volume of a conventional gas reservoir because coal has a large surface area. Another advantage of coalseams is that not only does such a process sequester CO_2, but methane is displaced which can be recovered and sold to help offset costs. This process is known as enhanced coalbed methane recovery, or ECBM. Advanced Resources International and their partners are using the only long-term, multi-well ECBM projects that exist in the world today to evaluate the viability of storing CO_2 in deep, unminable coal seams. The knowledge gained from studying these projects is being coupled with fundamental research to verify and validate gas storage mechanisms in coal reservoirs, and to develop a screening model to assess CO_2 sequestration potential in other promising coal basins of the U.S.

The two field pilots, the Allison Unit (operated by Burlington Resources) and the Tiffany Unit (operated by BP) are demonstrating CO_2 and nitrogen (N_2) ECBM recovery technology respectively. The interest in understanding how N_2 affects the process has important implications for power plant flue gas injection, since N_2 is the primary constituent of flue gas. Currently, the cost of separating CO_2 from flue gas is very high. Another reason for considering CO_2/N_2 is that N_2 is also an effective methane displacer, improving methane recoveries and further decreasing the net cost of CO_2 sequestration. This project is providing valuable new information to improve the understanding of formation behavior with CO_2 injection via fundamental laboratory and theoretical research, leading to the ability to predict results and optimize the process through reservoir modeling.

Primary Project Goal

The primary goal of this project is to develop a technical understanding of the CO_2-sequestration/ECBM process by performing fundamental R&D on coal reservoir behavior, studying the two field projects, and transferring that new knowledge to industry by developing an easy-to-use screening model that can quickly assess the feasibility of CO_2 sequestration at any given site based on coal seam data and injected gas properties.

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PROJECT WEBSITE

www.coal-seq.com

PARTNERS AND PERFORMERS

Advanced Resources International

Burlington Resources

BP

RECOPOL

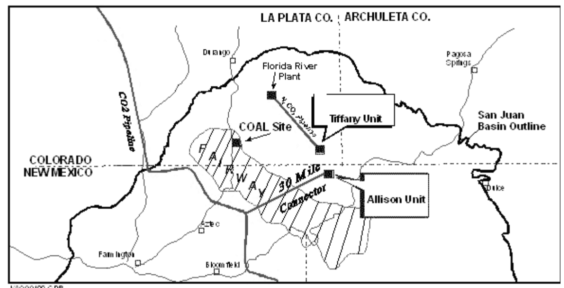
COST

Total Project Value
$7.3 million

DOE/Non-DOE Share
$2.5 million/$4.8 million

Objectives

- Perform fundamental research regarding multi-component sorption and flow behavior in various coal types, and develop predictive models of coal reservoir behavior with CO_2 injection.
- Demonstrate N_2/CO_2 ECBM recovery and CO_2 sequestration in deep, unminable coalbeds.
- Perform a capacity and economic assessment of the potential for CO_2 sequestration in deep, unmineable coal seams across the U.S.
- Develop a software model that can be used by industry to screen site-specific sequestration opportunities in coalbeds.
- Transfer results to a broad industrial base.



Location of the Tiffany and Allison Units

Accomplishments

The field studies have demonstrated that ECBM via CO_2/N_2 injection and CO_2 sequestration in coal seams is technically feasible. Field and laboratory data have provided important new insights on the process, such as the tendency for coal to "swell" when it comes into contact with CO_2, reducing injectivity. New light has also been shed on the processes of methane displacement by CO_2. These findings will have important implications for designing and implementing future CO_2-sequestration/ECBM projects, and are being incorporated into the project screening model. A national assessment has indicated that this approach has the potential to sequester 90 billion tonnes of CO_2, and provide an additional 150 trillion cubic feet of gas supply for the U.S.

Benefits

The knowledge gained from this project will benefit the electric power generation industry by providing verifiable and valid CO_2 storage mechanisms in coal reservoirs, as well as a new source of clean gas supply. The ability to take advantage of these opportunities will be facilitated by the development of a screening model to assess CO_2 sequestration and ECBM potential.

CO_2 Injector Well at the Allison Unit

Project 228.pmd

PROJECT

facts

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

Sequestration

02/2004

ENHANCED COAL BED METHANE PRODUCTION AND SEQUESTRATION OF CO_2 IN UNMINEABLE COAL SEAMS

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

David Hyman
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-6572
david.hyman@netl.doe.gov

Frank Burke
Project Manager
CONSOL Energy
4000 Brownsville Road
South Park, PA 15129
412-854-6676
frankburke@consolenergy.com

Background

CONSOL Energy, Inc. will demonstrate a novel drilling and production process that reduces potential methane emissions from coal mining, produces usable methane (natural gas), and creates a sequestration sink for carbon dioxide (CO_2) in unmineable coal seams. CONSOL's project will employ a slant-hole drilling technique to drain coalbed methane from a mineable coal seam and an underlying unmineambe coal seam. Upon drainage of 50-60 percent of the coalbed methane, some of the wells will be used for CO_2 injection to sequester the CO_2 in the unmineable seam, while stimulating addition methane production. The technique starts with a vertical well drilled from the surface followed by a guided borehole that extends up to 3,000 feet horizontally in the coal seam, allowing for production over a large area from relatively few surface locations.

The project will involve development of a 206.6 acre area involving two coal seams. The lower seam is an unmineable seam that will be degassed and eventually injected with CO_2. The upper seam is a mineable coal that will be degassed to produce coal bed methane, thus avoiding methane emissions when the seam is mined. The upper mineable seam will be isolated from the lower unmineable seam in which CO_2 injection will take place to prevent CO_2 migration into the mineable seam.

Picture of the North degassing wells

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

CONSOL Energy

COST

Total Project Value:
$12,642,000

DOE/Non-DOE Share:
$8,696,000 / $3,945,000

Primary Project Goal

The primary goal of this project is to evaluate the effectiveness and economics of carbon sequestration in an unmineable coal seam.

Objectives

- Demonstrate the application of coal seam methane production technology using novel slant hole drilling to degasify an unmineable coal seam
- Use the sale of methane to reduce the cost of carbon dioxide sequestration
- Sequester carbon dioxide in a degassed, unmineable coal seam
- Demonstrate that the carbon dioxide remains sequestered in the coal seam in which it was injected

Accomplishments

- The two degassing wells in the Pittsburgh Seam completed; degassing wells in the upper Freeport seam have been drilled and completed
- Dewatering and degassing of wells have begun
- Site preparation of the South Well site was completed
- Central Well site revised wells permitted by West Virginia Department of Environmental Protection

Benefits

This project will provide a documented case study of the effectiveness and economics of carbon sequestration in an unmineable coal seam. The results can be used not only by mining and power generation companies who wish to sequester carbon dioxide in unmineable coal seams but also by regulatory agencies and the public to aid in policy and permitting decisions.

Proj249.pmd

PROJECT

facts

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

02/2004

Analysis of Devonian Black Shale in Kentucky for Potential Carbon Dioxide Sequestration and Enhanced Natural Gas Production

Contact Points

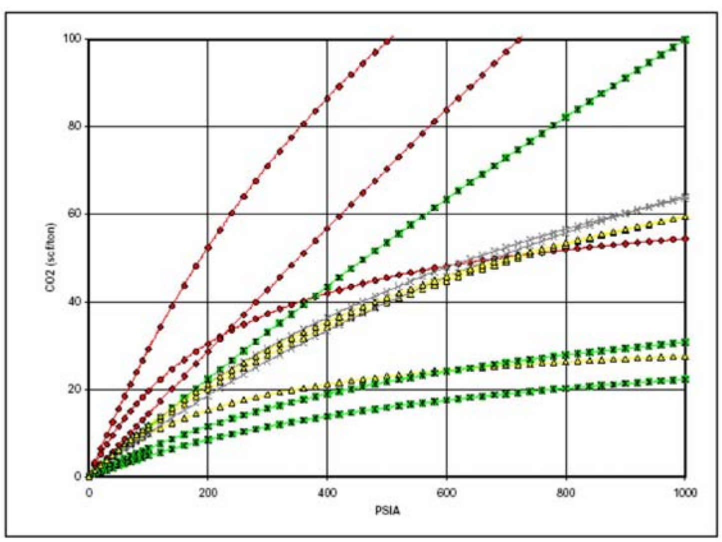
Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

David Hyman
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-6572
david.hyman@netl.doe.gov

Brandon C. Nuttall
University of Kentucky Research Foundation
Center for Applied Energy Research
201 Kinkead Hall, 2nd Floor
Main Campus
Lexington, KY 40506
606-257-0272

Background

Global climate change is an area of increasing concern, and many scientists believe the cause is due, at least in part, to increased emissions of CO_2, especially from the combustion of fossil fuels. These concerns are driving initiatives to develop carbon management technologies. One promising approach is geologic sequestration of CO_2. Options being investigated include sequestration in saline aquifers, oil and gas reservoirs, and unminable coal seams. In unminable coal seams, CO_2 is injected into the seam and is adsorbed on the surface of the coal, displacing methane that is recovered and sold to help offset sequestration costs. In analogy with sequestration in coal seams, another option may be sequestration in Devonian black shales, organic-rich rocks that serve as both a source and trap for natural gas. Most of the natural gas is adsorbed on clay or kerogen surfaces, very similar to the way methane is stored within coal beds. It has been demonstrated in gassy coals that, on average, CO_2 is preferentially adsorbed, displacing methane at a ratio of about one molecule of methane for two molecules of CO_2. Black shales may similarly desorb methane in the presence of adsorbing CO_2. If this is the case, the black shales of Kentucky could be a viable geologic sink for CO_2, and their extensive occurrence in Paleozoic basins across North America would make them an attractive regional target for economic CO_2 storage and enhanced natural gas production.



Absorption Isotherms of Devonian Black Shales. Several samples exhibit unexpectedly high measureed values for the adxorbed volume of CO_2

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

University of Kentucky Research Foundation and Kentucky Geological Survey

COST

Total Project Value:
$532,966

DOE/Non-DOE Share:
$364,453 / $168,513

Primary Project Goal

To test the hypothesis that organic-rich shales can adsorb significant amounts of CO_2 while releasing methane. This will be accomplished by examining core samples of Devonian shales for CO_2 adsorption capacity and developing a technique for estimating the CO_2 sequestration potential of shales in Kentucky.

Objectives

- To characterize the petrology, total organic content, and elemental composition of selected shale samples, and to correlate these properties with CO_2 adsorption capacity.
- To determine CO_2 adsorption isotherms of these samples.
- To determine the relationship between CO_2 adsorption and CH_4 desorption.
- To locate zones within shale deposits that have high CO_2 adsorption capacities.
- To delineate the vertical and aerial extent of these zones.

Accomplishments

A literature search has been completed, and a bibliography of articles and papers pertinent to shales has been prepared. Selected shale samples have been analyzed and characterized. A preliminary estimate has been prepared of the potential for CO_2 sequestration in the shales of Kentucky.

Drill cuttings and cores were selected from the Kentucky Geological Survey Well Sample and Core Library, and methane and CO_2 adsorption analyses are being performed to determine the gas storage potential of these shales and to identify shale facies with the most sequestration potential. In addition, sidewall core samples are being acquired to investigate specific black-shale facies, their potential CO_2 uptake, and the resulting displacement of methane. Advanced logging techniques (elemental capture spectroscopy) are being investigated for possible correlations between adsorption capacity and geophysical log measurements.

Measured adsorption isotherm data range from 37.5 to 2,077 scf/ton of shale. At 500 psia, adsorption capacity of the Lower Huron Member of the shale is 72 scf/ton. Initial estimates indicate a sequestration capacity of 5.3 billion tons of CO_2 in the Lower Huron Member of the Ohio shale in parts of Eastern Kentucky and as much as 28 billion tons total in the deeper and thicker portions of the Devonian shales in Kentucky.

Benefits

To meet the President's goal of decreasing CO_2 emissions per dollar of GDP by 18% by 2012, it will probably be necessary to sequester CO_2 in geologic and terrestrial sinks. Having a range of viable options for CO_2 sequestration increases the likelihood of successfully meeting the President's goal. This project will evaluate an option that has received relatively little attention—storing CO_2 in shale deposits, while simultaneously producing natural gas, the sale of which can help offset sequestration costs. The potential capacity of shales to sequester CO_2 is very large, and being able to store CO_2 in shales could significantly increase the life of fossil fuel based power plants, if reductions in anthropogenic greenhouse gas emissions are required.

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

CO_2 SEQUESTRATION POTENTIAL OF TEXAS LOW-RANK COALS

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

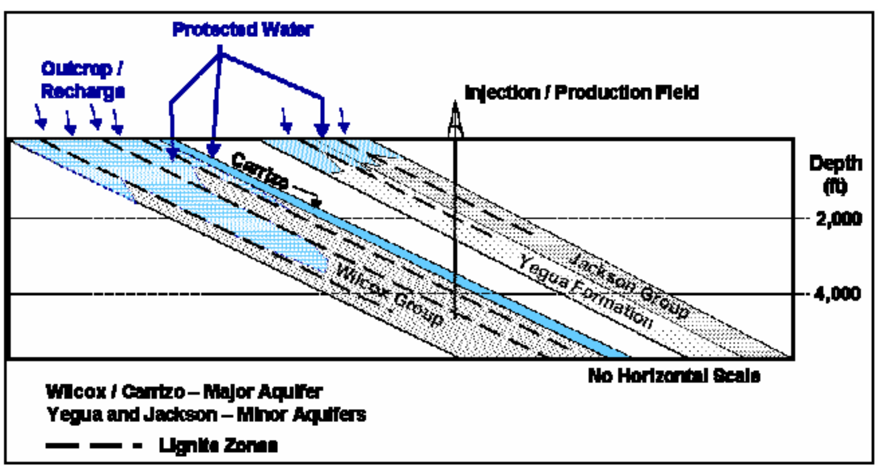
David Hyman
Project Manager
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-6572
david.hyman@netl.doe.gov

Duane McVay
Texas Engineering Experiment Station
006 Wisenbaker Engr. Res. Ctr
College Station, TX 77843
979-862-8466
mcvay@spindletop.tamu.edu

Background

Fossil fuel combustion is the primary source of emissions of carbon dioxide (CO_2), a major greenhouse gas. Sequestration of CO_2 by injecting it into geologic formations, such as coal seams, may offer a viable method for reducing atmospheric CO_2 emissions. Injection into coal seams has the potential added benefit of enhanced coalbed methane recovery. The potential for CO_2 sequestration in low-rank coals, while as yet undetermined, is known to differ significantly from that for bituminous coals. To evaluate the feasibility and the environmental, technical, and economic impacts of CO_2 sequestration in Texas low-rank coal beds, the Texas Engineering Experimental Station is conducting a two-year study to characterize coals located near major electrical power plants. Potential CO_2 sequestration sites have been identified in coals near three Texas power plants. These power plants emit over 30 million metric tons of CO_2 annually, accounting for nearly 15 % of Texas' point-source emissions.

It has been widely reported that coals will adsorb approximately twice as much CO_2 as methane, but tests of a limited number of samples from the Northern Great Plains and Texas indicate that low-rank coals may adsorb 6-18 times as much CO_2 as methane. CO_2 injection can improve methane recovery and help maintain reservoir pressure, thus offsetting operating costs by reducing the amount of gas compression required.



Schematic presentation of multizone sequestration/ production potential at some sites.

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

Texas Engineering Experiment Station

COST

Total Project Value

$450,000

DOE/Non-DOE Share

$360,000/$90,000

Primary Project Goal

The primary goal this project is to evaluate the feasibility and environmental and economic impacts of sequestration of CO_2 in Texas low-rank coal seams.

Objectives

Specific project objectives are to:

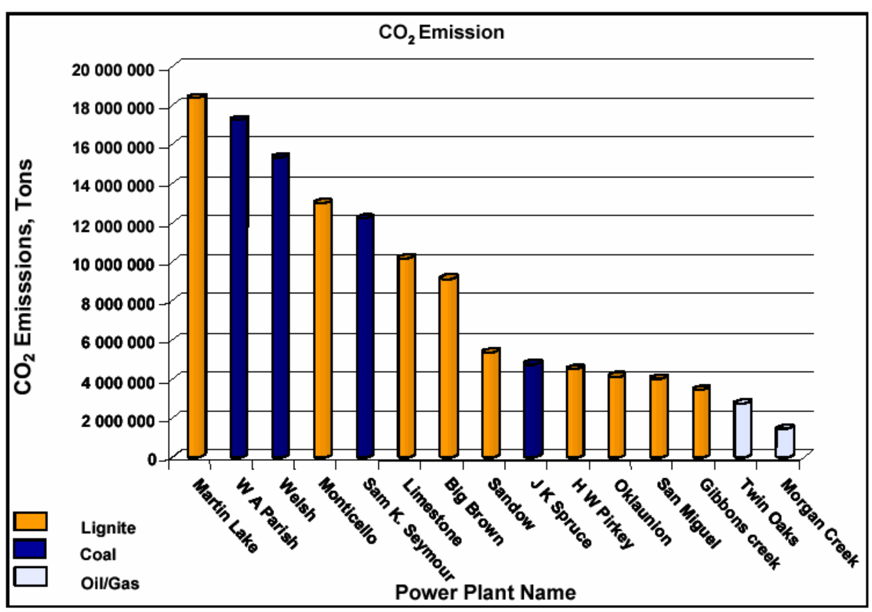
- Determine the technical and economic feasibility and volume of CO_2 that could be sequestrated in Texas coal seams.
- Determine locations and quantities of anthropogenic CO_2 sources near possible coal injection sites.
- Determine the potential for enhanced coalbed methane recovery as an added benefit of sequestration.

Accomplishments

Potential sites for geologic sequestration of CO_2 with possibilities for enhanced recovery of coalbed methane near three of Texas' largest power plants have been developed. As an example, on the basis of preliminary reservoir simulation at one site using assumed permeability, it was estimated that the Gibbons Creek power plant could sequester all the CO_2 it generated for 11 years using 360 injection wells in nearby low-rank coal seams while producing 180 billion cubic feet of methane.

Benefits

Texas is one of the largest emitters of CO_2 in the U.S. However, Texas also has huge reserves of low-rank coal, and much of this coal is in deep seams in close proximity to large power plants. Thus, there is great potential for sequestering CO_2 in these coal seams while simultaneously producing large volumes of coalbed methane to help offset sequestration costs. Such projects could make a significant contribution towards meeting the goal of reducing greenhouse gas intensity (pounds of CO_2 emitted per dollar of GDP) by 18% by 2012.



Amount of CO_2 emitted and fuel type by power plant, 15 largest Texas CO_2 emitters.

*Factsheet Under Development

Reactive, Multi-phase Behavior of CO_2 in Saline Aquifers Beneath the Colorado Plateau*
-University of Utah

Page left blank to accommodate 2-sided printing

PROJECT facts

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

Sequestration

03/2003

NETL

STORAGE OF CO_2 IN THE GEOLOGIC FORMATIONS IN THE OHIO RIVER VALLEY REGION

Background

Storage of carbon dioxide (CO_2) in a dense, supercritical phase in deep saline sandstone formations is deemed to be a very promising long-term option for sequestration. Deep saline formations are among the largest and most widely available potential reservoirs for long-term storage. Usable formations are known to exist underneath much of the continental U.S. and under the oceans. In both locations, these formations appear to have abundant disposal capacity. Moreover, many of these formations are often located in close proximity to major point sources of CO_2 emissions such as fossil-fuel power plants, which has the benefit of reducing transportation costs of CO_2 to the injection site.

During the 1990s, Battelle researchers were some of the first scientists to be supported by the U.S. Department of Energy's National Energy Technology Laboratory to explore the potential of using deep geologic formations as a means of sequestering CO_2. The current project is in Phase III of Battelle's research; the first two Phases were funded under the "Global Climate Change - Novel Concepts for Management of Greenhouse Gases" program. Commencement of this effort underscores the progression of DOE's geologic sequestration program from computer and laboratory assessment towards pilot-scale testing and verification. Phase III is focused on a site characterization (surface and subsurface) for possible injection of CO_2 into a suitable formation.

In this project, the research team is planning a field study to determine whether the deep rock layers in the Ohio River Valley are suitable for storing carbon dioxide. The research team includes American Electric Power (AEP), which owns and operates the Mountaineer plant (the host site for the research project); Battelle, a non-profit organization, headquartered in Columbus Ohio, and is a global leader in technology development; the U.S. Department of Energy; BP; Schlumberger, and Pacific Northwest National Laboratory. The Ohio Coal Development Office of the Ohio Department of Development (OCDO) is also providing support to the project, given the potential to address future carbon emissions from the many coal-based electricity power plants in Ohio and to retain the jobs that these plants and Ohio coal mines support. Additional technical support is being provided by researchers from the West Virginia University, the Ohio Geological Survey, and several technology vendors. If the studies show that storing carbon dioxide deep underground in the Ohio River Valley will be safe, practicable, and effective, AEP and its partners will decide whether to go to the next stage.

Primary Project Goal

The project will involve site assessment to develop the baseline information necessary to make decisions about a potential CO_2 geologic disposal field test and verification experiment at the site. This project will be focused in the Ohio River Valley, which is home to the largest concentration of fossil-fuel fired electricity generation in the nation. Additionally, the potential for long-term sequestration of CO_2 in deep, regional sandstone formations and the integrity of overlying caprock will be evaluated for future sequestration projects. No CO_2 injection is planned during this phase.

CONTACT POINTS

Scott M. Klara
Sequestration Product Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Neeraj Gupta
Principal Investigator
Battelle Memorial Institute
505 King Avenue
Columbus, OH 43201
614-424-3820
gupta@battelle.org

Charles W. Byrer
Project Manager: Environmental Projects Division
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-4547
charles.byrer@netl.doe.gov

CUSTOMER SERVICE

800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS AND PERFORMERS

Battelle Memorial Institute

American Electric Power

Pacific Northwest National Laboratory

BP

Ohio Coal Development Office of the Ohio Department of Development

Schlumberger

Ohio Geological Survey

West Virginia University

TOTAL ESTIMATED COST

Total Project Value	$4,172,441
DOE	$3,151,441
Non-DOE Share	$1,021,000

STORAGE OF CO_2 IN THE GEOLOGIC FORMATIONS IN THE OHIO RIVER VALLEY REGION

Objectives

- Thoroughly assess the geologic environment in the Ohio River Valley in order to site a field test.
- Conduct a 2-dimensional seismic survey to delineate subsurface geologic structures.
- Drill an exploratory deep well to collect scientific data to assess the potential for conducting a CO_2 storage test at the site.
- Conduct tests to comprehensively characterize the reservoirs, caprocks, and overlying layers, thereby developing a thorough understanding of the geology, hydrogeology, and geochemistry at the site.
- Prepare the necessary permits and regulatory documents to allow use of the deep well to inject CO_2 captured from a nearby coal-fired power plant.
- Develop and apply a comprehensive Risk Analysis and Stakeholder Involvement Process for the capture, transport, injection, and long-term storage of CO_2 at the field demonstration site.
- Develop a comprehensive monitoring plan to ensure the safe, long-term isolation of CO_2 in deep geologic formations.

Prior Accomplishments

Prior research by Battelle scientists leading up to the current project includes:

- Regional data compilation, reservoir and geochemical simulations, geochemical experiments, and seismic aspects reports have been completed.
- A detailed report on engineering and economic aspects for CO_2 capture and storage has been completed.
- Regional-scale assessments in the Midwest and other regions show that there is enormous potential sequestration capacity in sedimentary basins with favorable formation thickness, hydrogeology, seismicity, and proximity to CO_2 sources. However, site-specific tests and characterization are needed to determined injection potential at individual locations.

Benefits


The Mountaineer Power Plant

Evaluating the feasibility of CO_2 storage at several different scales will allow the energy industry to prove the viability of an evolving U.S. technology that will allow fossil-fuel fired power plants to continue operating well into the future as our nation develops a strategy to deal with the buildup of greenhouse gases in the atmosphere. The project approach will allow the U.S. to more rapidly move the concept of carbon capture and geologic disposal from the laboratory to an industrial-scale demonstration. If the research shows that storage is feasible, it could offer a way for many utilities around the country to significantly reduce their carbon emissions. It will be especially beneficial to states such as West Virginia, Ohio, and many of the large industrial States in the Midwest, which depend heavily on coal for electricity generation. Finally, all aspects of the current project including field characterization, testing, permitting, and monitoring plans development will provide a protocol for similar investigations at other locations in the future.

Proj227.pmd

Geological Sequestration of CO_2: The GEO-SEQ Project

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Sally M. Benson
Principal Investigator: Earth Sciences Division
Lawrence Berkeley National Laboratory
1 Cyclotron Road
Mailstop 50A-4112
Berkeley, CA 94720
510-486-5875
SMBenson@lbl.gov

Charles W. Byrer
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880
304-285-4547
charles.byrer@netl.doe.gov

Background

The GEO-SEQ Project has carried out eight separate, but related, tasks that provide new methods and approaches for reducing the cost and risk of geologic sequestration. The results from these tasks provide the basis for the development of a set of best practices for measurement, monitoring, and verification (MMV) of geologic sequestration. The eight tasks included in this project are:

- Co-optimization of carbon sequestration with oil and gas recovery
- Carbon sequestration with enhanced gas recovery
- Co-disposal of CO_2, H_2S, NOx, and SO_2
- Evaluation of geophysical monitoring technologies
- Application of natural and introduced tracers
- Enhancement of numerical simulators for greenhouse gas sequestration in deep unminable coal seams and in oil, gas, and brine formations
- Improving the methodology for capacity assessment
- Frio pilot test

The current focus is a collaboration with the Texas Bureau of Economic Geology to conduct the Frio pilot brine formation CO_2 injection test. The pilot test involves injection of about 3,000 tons of CO_2 into the upper Frio at a depth of about 1,500 m in the South Liberty Field, near Houston, Texas.

Primary Project Goal

The goal is to lower the cost, risk, and time to implement a geologic CO_2 sequestration project. Effective interaction with, and technology transfer to, industrial partners and demonstrable results in each area within three years are paramount goals.

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

Lawrence Berkeley National Laboratory (LBNL)

Lawrence Livermore National Laboratory (LLNL)

Oak Ridge National Laboratory (ORNL)

Netherlands Institute of Geoscience

Stanford University

University of Texas at Austin-Bureau of Economic Geology

Alberta Research Council

BP

ChevronTexaco

En Cana

Statoil

COST

Total Project Value
$15,025,000

DOE/Non-DOE Share
$3,225,000/
$11,800,000

Objectives

- To develop methods to optimize value-added sequestration in oil and gas formations
- To lower the cost of sequestration by understanding the relationship between the cost of separation, compression, transportation, and the well-field and the geologic properties of the injection formation
- To provide an optimized set of monitoring technologies, ready for full-scale field demonstration in oil, gas, and brine formations
- To improve computer simulation models for predicting the performance of CO_2 sequestration in oil, gas, brine, and coal bed formations
- To improve the methodology and information base for assessing the sequestration capacity of oil, gas, brine, and unmineable coal formations
- To conduct an outreach program to provide information to schools and stakeholders

Accomplishments

Screening criteria for selection of oil reservoirs that would co-optimize enhanced oil recovery (EOR) and CO_2 sequestration have been developed, along with an engineering approach to increase CO_2 storage during EOR. Numerical simulation of CO_2 storage with enhanced gas recovery (CSEGR) in depleted gas reservoirs has shown the concept to be viable. Additionally, potential reaction products have been determined using reaction-progress thermodynamic/kinetic calculations. This data is the basis for evaluating the impact of impure waste streams.

A methodology for site specific selection of monitoring technologies was established and demonstrated. Also, the first test of the joint application of crosswell seismic and crosswell electromagnetic measurements for CO_2 monitoring was completed. The baseline data needed for interpretation of tracers used to monitor reservoir processes has been obtained through laboratory isotopic-partitioning experiments and mass-balance isotopic-reaction calculations.

Reservoir simulator code comparison studies for oil, gas, brine, and coal bed reservoirs are underway, providing a mechanism for establishing current capabilities, areas needing improvement, and confidence in simulation models.

A new definition of formation capacity, incorporating intrinsic rock capacity, geometric capacity, formation heterogeneity, and rock porosity was developed for use in assessing sequestration capacity. An assessment of CO_2 sequestration capacity in California was carried out, and factors affecting sequestration capacity of the Frio formation in Texas have been evaluated.

Benefits

The benefits of this project will be lower sequestration costs, lower sequestration risk, decreased time to implementation, and increased public acceptance. By optimizing technologies with collateral benefits for fossil fuel production, lower sequestration costs can be achieved. The risk associated with sequestration can be minimized if needed site selection information is provided. Confidence and safety are increased by demonstrating innovative monitoring and tracking technologies. Pursuing early opportunities to do pilot tests and gaining acceptance can reduce time to implementation by the private sector. Finally, public acceptance can be increased through assuring stakeholders and the public of decreased costs and the certainty of storage permanence.

PROJECT facts

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

Sequestration

12/2004

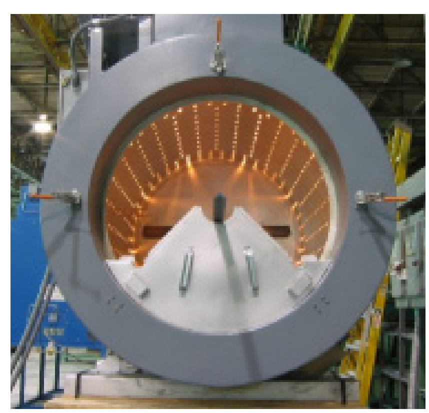
Strategies for Controlling Coal Permeability in CO_2-Enhanced Coalbed Methane Recovery

Background

Evidence is mounting that rising levels of atmospheric CO_2, caused primarily by combustion of fossil fuels, are leading to global warming. To address this problem, many nations are developing plans for decreasing CO_2 emissions to the atmosphere. The principal approaches under consideration are improving energy efficiency, making greater use of non-fossil energy sources, and creating economically viable technologies for capture and long-term storage of CO_2. The latter strategy, commonly known as CO_2 sequestration, will keep a large quantity of CO_2 out of the Earth's atmosphere for hundreds to thousands of years. Consequently, it permits continued use of high-carbon fossil fuels to generate electrical power while ensuring that CO_2 releases to the atmosphere are reduced.

A potentially attractive means for geologic CO_2 sequestration is injection of CO_2 into underground reservoirs. The primary candidates are active or depleted oil and gas fields, deep brine formations, and unmineable coalbeds. To date, studies to determine the feasibility of geologic CO_2 sequestration have focused on oil and gas fields and deep brine formations. However, four characteristics of deep unmineable coalbeds make them extremely attractive for wide-scale CO_2 sequestration:

1. Unmineable coal seams are widely distributed across the U.S.
2. When CO_2 is injected into a coalbed, it efficiently displaces adsorbed methane (CH_4). Therefore, CO_2 sequestration and coalbed methane (CBM) production are synergistic technologies, with the extra natural gas produced serving to offset some of the costs of CO_2 injection.
3. After injection, CO_2 remains tightly bound to coal surfaces; therefore, there is little risk that, over time, it will leak to overlying strata or to the surface. This is an enormous advantage over CO_2 storage in deep saline formations, where escape of gas through caprock is a potentially serious problem.
4. Many unmineable coal seams are located near coal-fired power plants, which are large point sources of CO_2. Thus, minimal pipeline transport would be required to deliver CO_2 to a suitable site for injection.



Endview of a 30-inch I.D., infrared forced-air convection oven custom designed and constructed for heating powdered and solid coal samples to temperatures attained in deep unmineable coalbeds.

CONTACTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Dawn M. Chapman
Project Director
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-4133
dawn.chapman@netl.doe.gov

James G. Blencoe
Oak Ridge National Laboratory
1 Bethel Valley Road
P.O. Box 2008
Oak Ridge, TN 37830
865-574-7041
blencoejg@ornl.gov

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

Oak Ridge National Laboratory (ORNL)

COST

Total Project Value
$600,000

DOE/Non-DOE Share
$600,000/$0

Benefits

If CO_2 emissions into the atmosphere from fossil fuel-fired power plants are to be controlled, suitable technologies for sequestering CO_2 must be developed. One very promising technique is CO_2-ECBM production. However, for this approach to be successfully pursued, much more information is needed on the behavior of coalbeds during and after CO_2 injection. This project will develop much of the needed data required to model CO_2-ECBM. These modeling efforts, along with demonstration programs, will establish the feasibility of CO_2-ECBM and the amount of natural gas that can be produced from such projects.

CBM recovery, accomplished principally by pumping formation water out of coalbeds, is a mature technology. In contrast, CO_2-enhanced CBM (CO_2-ECBM) recovery is a recent concept that has been demonstrated at only a few field sites. Therefore, vigorous fundamental and applied research programs are needed to fill major knowledge gaps.

Brought to full fruition, CO_2-ECBM could become a leading technology for combined CO_2 sequestration and enhanced methane recovery. However, to enable reliable numerical modeling of CO_2-ECBM production, the effects of CO_2 injection rate, formation temperature, total gas pressure, and gas composition on coal swelling and shrinkage, and sorption/desorption of gases on coal surfaces, must be known quantitatively. The impacts of these effects cannot be predicted accurately by current methods of reservoir modeling and simulation; consequently, an experimental program is needed to obtain the required information.

Due to their special importance, this project is particularly concerned with factors that affect coal permeability when CO_2 is injected into a subsurface coalbed. The major permeability-affecting parameters are likely to be: initial coal porosity and permeability; formation temperature; the rate of CO_2 injection; time-dependent local gas composition, including moisture content; and the characteristics of the organic and inorganic surfaces of the coal into which mixed CO_2-CH_4-H_2O gas penetrates. The results of CO_2 influx will include sorption/desorption of gas species, coal swelling and shrinkage, migration of CH_4 toward production wells and other regions of lower gas pressure, and drying of the coal near the point of CO_2 injection. These effects will have time varying, interacting impacts on coal permeability. Therefore, sorting out the individual and collective effects of factors that affect coal permeability during CO_2-ECBM operations is absolutely essential for reliable prediction and full optimization of CO_2 sequestration in, and enhanced methane recovery from, subsurface coalbeds.

Primary Project Goal

The primary goal is to acquire the critically important technical information needed to assess the feasibility of sequestering CO_2 in deep unmineable coalbeds.

Objectives

- To acquire and characterize sections of coal core obtained from the Black Warrior Basin in westcentral Alabama.
- To complete a set of sorption/desorption experiments on powdered coal samples from the Black Warrior Basin.
- To complete a set of gas permeability experiments on uncrushed coal samples from the Black Warrior Basin to determine the effects of: (1) the rate of CO_2 injection; (2) adsorption of CO_2 onto, and desorption of CH_4 and H_2O from, coal surfaces; (3) coal swelling and shrinkage due to gas adsorption and desorption; and (4) drying of moist coal near the site of CO_2 injection.

Accomplishments

Unique, custom-designed laboratory facilities have been constructed to measure the densities of mixed CO_2-CH_4 gases at 20-50°C, 0-2000 psi, and to determine the factors that have the greatest influence on subsurface coal permeability during CO_2-ECBM operations. The measurements being made with the new equipment are addressing critical information needs for current and future U.S. CO_2-ECBM demonstration sites.

Proj314.pmd

11/2004

PROJECT facts

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

FEASIBILITY OF LARGE-SCALE CO_2 OCEAN SEQUESTRATION

Background

The disposal in the deep ocean of CO_2 generated by the combustion of fossil fuels has long been discussed as a speculative option for controlling greenhouse gas induced climate change. Although models of deep ocean sequestration have been formulated and laboratory simulations have been carried out, few direct oceanic experiments have been reported. With the availability of advanced Remotely Operated Vehicle (ROV) technology, it has now become possible to carry out controlled releases of many chemical species in the deep ocean, and to observe and measure the processes taking place.

The Monterey Bay Aquarium Research Institute (MBARI) is investigating the chemical, and physical behavior of, and biological responses to, hydrates on the sea floor at a depths up to 3,600 m. Many people are aware of methane hydrates, ice like complexes of water and methane, but are unaware that, under the proper conditions, CO_2 can also form hydrates. The storage of CO_2 in hydrate pools at the bottom of the ocean is being investigated. Four research cruises using the ROV to study CO_2 hydrate ocean storage off Monterey Bay have been completed. The physical chemistry and biological effects of hydrate formation have been studied in the deep ocean by means of small-scale batch experiments.

The research group at Washington University, with MBARI, is using *in situ* Raman spectroscopy to carry out the first direct in situ analysis on the sea floor of CO_2 hydrates, the entrained and surrounding fluids, and the sediments adjacent to the hydrates. Information on hydrate/sediment interaction is essential for the evaluation of ocean sequestration of CO_2.

Primary Project Goal

The primary goal of this project is to investigate the chemical, physical, and biological behavior of CO_2 hydrates in the deep ocean. These data are necessary to help evaluate the storing CO_2 in hydrate pools at the bottom of the ocean, a possibility under consideration.

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Heino Beckert
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-4132
heino.beckert@netl.doe.gov

Peter G. Brewer
Monterey Bay Aquarium Research Institute
7700 Sandholdt Road
Moss Landing, CA 95039
831-775-1706
brpe@mbari.org

PROJECT PARTNERS

Monterey Bay Aquarium Research Institute (MBARI)

Washington University at St. Louis

COST

Total Project Value: $1,263,755

DOE: $ 970,041
Non-DOE Share: $ 293,714

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

Objectives

Three field experiments will be conducted to study:

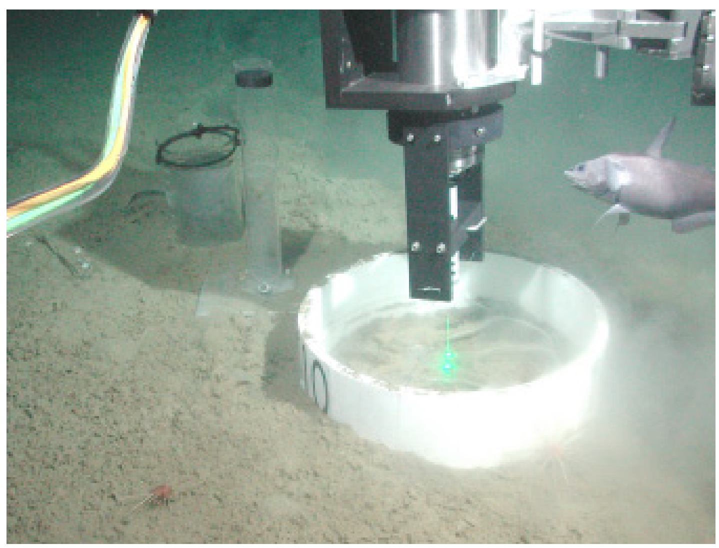
- Long term fate of CO_2 and CO_2 hydrates on the sea floor
- Biological responses to the disposed material
- Geochemical interactions with sediments and pore waters

Accomplishments

MBARI used a small scale delivery system with a capacity of 56 liters to study CO_2 interactions with the ocean. Four controlled delivery dives were executed with the CO_2 delivered to a central corral complex. Results showed a strong tidal periodicity in the water plume of lowered pH and a complex set of biological responses. Below a depth of about 3,000 m, the density of liquid CO_2 exceeds that of seawater, and the CO_2 is quickly converted into solid hydrate by reaction with the surrounding water.

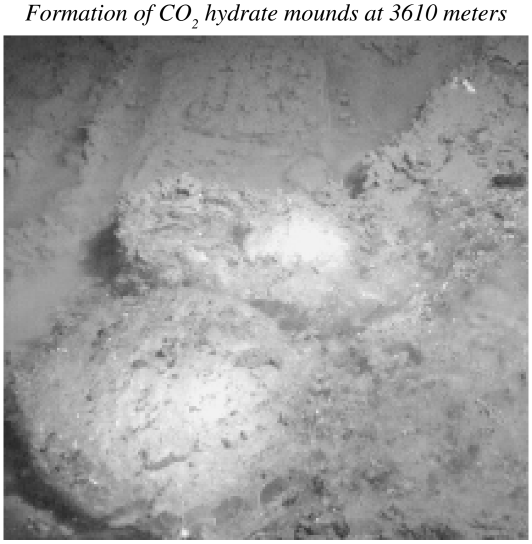
Benefits

This project will provide further understanding of the behavior of CO_2 within the ocean environment. Hydrate pools at the bottom of the ocean have the potential for long-term storage of large quantities of CO_2.



Testing the waters: An experiment to investigate the fundamental science of ocean CO_2 sequestration at a depth of 3,600m off the coast of California. A small pool of liquid CO_2 is sensed by the beam of a laser Raman spectrometer to record the chemical status of the material. A laboratory beaker and measuring cylinder, also used for experiments are close by. A Pacific Grenadier fish observes the activity. This sea floor laboratory is controlled by a remotely operated vehicle.

Formation of CO_2 hydrate mounds at 3610 meters



Proj237.pmd

PROJECT facts

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

Sequestration

02/2004

NETL

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Dawn Chapman
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-4133
Dawn.Chapman@netl.doe.gov

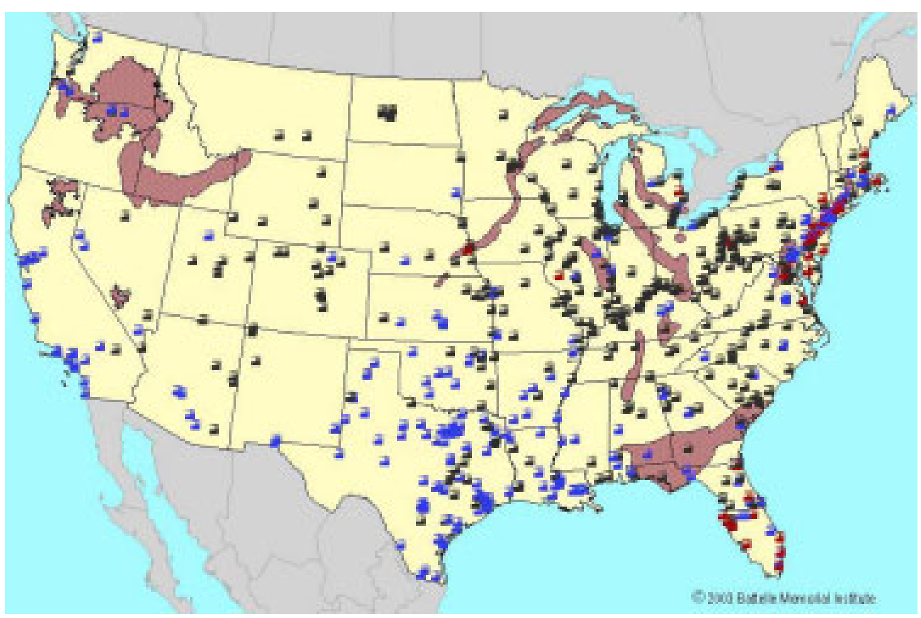
Bernard McGrail
Pacific Northwest National Laboratory
902 Battelle Boulevard
Richland, WA 99352
509-376-9193

CO_2 Sequestration in Basalt Formations

Background

There is growing concern that the buildup of greenhouse gases, especially CO_2, in the atmosphere is contributing to global climate change. One option for mitigating this effect is to sequester CO_2 in geologic formations. Numerous site assessments for geologic sequestration of CO_2 have been conducted in virtually every region of the U.S. For the most part, these studies have involved storing CO_2 in saline aquifers, deep coal seams, of depleted oil and gas reservoirs. Another option, however, is basalt formations. Basalt is an aluminum silicate that contains basic ions, such as sodium and calcium, that can combine with CO_2.

Basalt formations have not received the attention they deserve with respect to their potential for permanent sequestration of anthropogenic CO_2. Major basalt formations that may be attractive for carbon sequestration occur in the Pacific Northwest, the Southeastern U.S., and at several other locations around the world. Unlike sedimentary rock formations that have received much attention, basalt formations have unique properties that will result in chemically trapping the injected CO_2, thus effectively and permanently isolating it from the atmosphere.



Distribution of major basalt formations in the U.S. along with coal (black), oil(red), and natural gas(blue) power plants

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

Pacific Northwest National Laboratory (PNNL)

COST

Total Project Value:
$400,000

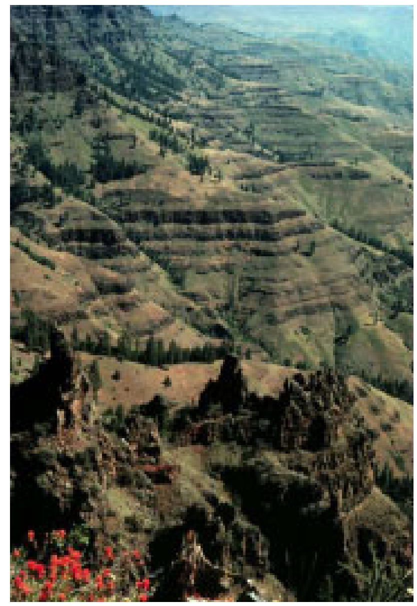
DOE/Non-DOE Share:
$400,000 / $0

Close-up picture of a basalt grain that has been reacted with supercritical CO_2 - the white crystals coating the grain are calcite.

Because of the very limited study of basalts for carbon sequestration, basic information on injectivity, storage capacity, and rate of conversion of gaseous CO_2 to solid carbonates is not available. Preliminary experiments conducted at Pacific Northwest National Laboratory (PNNL) have confirmed that carbonate mineral formation occurs when basalts from the Columbia River Basalt Group (CRBG) are exposed to supercritical CO_2. However, insufficient data have been generated from these experiments to permit reliable projections of CO_2 conversion rates under large-scale sequestration conditions. Information is also lacking on the ability of basalts from other parts of the U.S. to support in situ mineralization reactions.

Primary Project Goal

The primary goal of this project is to evaluate the capacity of basalt formations for CO_2 storage and to determine the rate of conversion of injected CO_2 to carbonates. The principal focus is on the Central Atlantic Mafic Province in the Southeastern U.S., but there is also interest in the Columbia River Basalt Group in the Pacific Northwest.



Picture of an outcrop of Columbia River Basalt showing the multiple layers resulting from the periodic lava eruptions

Objectives

- To determine mineralization kinetics for CO_2 conversion to carbonates.
- To conduct tomography on the Basalt Flow Top.
- To determine CO_2 storage capacity in basalt formations.

Accomplishments

- Completed a set of dissolution kinetics measurements as a function of temperature and pH on Columbia River basalt.
- Carbonate mineralization was verified by optical and scanning electron microscopy, x-ray diffraction, and Raman spectroscopy.
- The reservoir capacity of the Columbia River Basalt Group was estimated using existing geologic data obtained from prior DOE-RW studies.
- Core samples and geologic data for the Central Atlantic Mafic Province basalts have been obtained.

Benefits

Because of concern over the impact of greenhouse gases, particularly CO_2, on global climate change, considerable effort is being expended evaluating the potential of CO_2 sequestration to mitigate the buildup of CO_2 in the atmosphere. Success of this project will expand the viable geologic options for CO_2 sequestration in the continental U.S. and provide heretofore unexplored options for CO_2 sequestration in developing countries, such as India and China.

Proj277.pmd

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

10/2004

International Collaboration on CO_2 Sequestration

Background

The concentration of CO_2 in the atmosphere has been increasing since the start of the industrial revolution due, in large part, to increased fossil fuel combustion. Because CO_2 is a greenhouse gas, its increased atmospheric concentration has generated concern about global climate change. One suggestion to address this issue is to capture CO_2 from stationary power sources and introduce it directly into the oceans, thus bypassing the slower biological and solubility cycles by which approximately 80 percent of the CO_2 that we currently emit will ultimately be absorbed by the oceans.

Among the issues requiring consideration before sequestering CO_2 in the oceans would become feasible, is the need to obtain high initial dilution of CO_2 in ocean water in order to minimize the excess concentration of dissolved inorganic carbon and, hence, the associated increase in pCO_2 and decrease in pH to which the aquatic biota would be exposed.

Although the overall project involves eleven tasks, the emphasis at MIT will be on the following four tasks: (1) preparation and testing of equipment for measurement and monitoring; (2) observing the performance of ocean field experiments; (3) analysis of data acquired during the experiments; and (4) collation of overall results obtained in the field experiments. This international effort involves five nations (the U.S., Japan, Norway, Canada, and Australia) and one private corporation (ABB of Switzerland). In the project agreement, the Massachusetts Institute of Technology (MIT) is designated as the Implementing Research Organization for the DOE.

Two-phase plumes play an important role in various scenarios for ocean sequestration (dispersing CO_2 as a buoyant liquid from either a bottom-mounted or ship-towed pipeline or as a negatively buoyant hydrate from a ship). Despite much research on related applications, understanding of these CO_2 flows is incomplete, especially concerning the phenomenon of plume peeling in a stratified ambient environment. To address this deficiency, a laboratory facility was built to obtain fundamental measurements of CO_2 plume behavior.

Primary Project Goal

The overall goal of this international effort toward reduction of greenhouse gases via ocean sequestration of CO_2 is to (1) investigate the technical feasibility of this approach to carbon management; (2) improve our understanding of the potential environmental impacts of ocean sequestration of CO_2; and (3) to minimize impacts associated with this sequestration technology on the marine biota.

MIT's primary activity, as part of this overall effort, is to conduct a series of laboratory experiments and to develop a mathematical model to describe a plume of liquid CO_2 dispersed from a nozzle in the deep ocean.

CONTACTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Heino Beckert
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-4132
heino.beckert@netl.doe.gov

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PRINCIPAL INVESTIGATOR

Dr. E. Eric Adams
MIT Dept. of Civil and Environmental Engineering
Room 48-216b
Cambridge, MA 02139
617-253-6595
eeadams@mit.edu

PARTNERS

Massachusetts Institute of Technology

Research laboratories in Japan, Norway, Canada, and Australia

COST

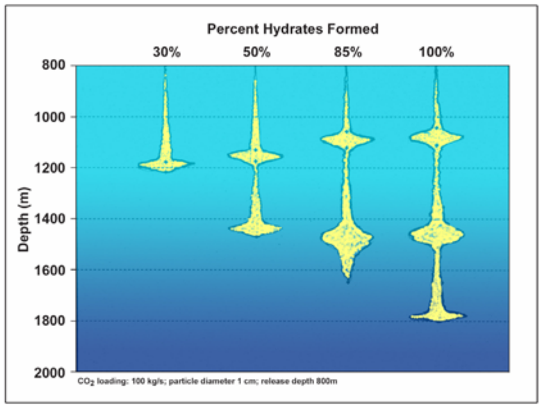
Total Project Value
$1,100,000

DOE/Non-DOE Share
$1,100,000/$0

Benefits

The consequences from global climate change and rising sea levels are potentially severe. Therefore, it is important to explore all options for mitigating the buildup of greenhouse gases in the atmosphere. One possibility is sequestration in the oceans. However, much more complete understanding of the environmental effects of this option need to be developed before ocean sequestration of CO_2 can be implemented. This project is aimed at providing that understanding.

While directly applicable to ocean carbon sequestration, results developed by this project will also provide guidance for the effective three-dimensional dispersal of other materials, such as nutrients for open water aquaculture and flocculants or algaecides for improving water clarity in reservoirs or town ponds.



A schematic depicting plume model results for sinking plumes of different hydrate composition

Snapshot of a sinking particle plume in the laboratory

Objectives

- To prepare and test instrumentation for the measurement and monitoring of CO_2 injection into the oceans.
- To better understand the phenomena occurring in two-phase plumes.
- To observe the performance of ocean field experiments.
- To analyze data acquired during field experiments.
- To collate overall results obtained from field experiments.
- To develop and validate a model of the behavior of CO_2 injected into the ocean.
- To participate in project management as a member of the Technical Committee.

Accomplishments

Quantitative data are being compared with a new analytical model which treats the flow as an upward-moving inner plume, coupled with an annular, downward-flowing outer plume. The model also includes CO_2-specific features, such as bubble/droplet mass transfer, solute dissolution effects on plume buoyancy, and change in total CO_2 concentration and pH. This double plume model was used to explore the fate of solid CO_2 hydrate particles released into the ocean for the purpose of CO_2 sequestration. Previous modeling results have been compared with those of researchers from Japan and Norway.

Mathematical models have been used to examine three dilution strategies that promote mixing in the longitudinal, lateral, and vertical directions. A point release of negatively buoyant solid CO_2 hydrate particles from a moving ship would achieve acceptable dilution near the source, while subsequent concentrations would be very low due to longitudinal mixing afforded by the ship's speed. A long, bottom-mounted diffuser, discharging buoyant liquid CO_2 droplets, can be designed for high lateral mixing, resulting in arbitrarily small near source concentrations, but because the resulting near field plume would be very wide, subsequent dilution would be slow. A stationary point release of hydrate particles achieves good vertical mixing, due to the negatively buoyant plume effect, resulting in intermediate local and subsequent concentrations.

Proj312.pmd

PROJECT facts

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

Sequestration

04/2004

LABORATORY INVESTIGATIONS IN SUPPORT OF CARBON DIOXIDE-LIMESTONE SEQUESTRATION IN THE OCEAN

Background

Many approaches have been proposed for the sequestration of CO_2. One idea, which has received much consideration, is that of storing CO_2 in the ocean. However, since liquid CO_2 is less dense than water and poorly miscible with water, the CO_2 must be injected at sufficient depth, so it will not buoy upward to approximately 500 m depth, where it would flash into vapor and reemerge into the atmosphere. Furthermore, when CO_2 dissolves in water it forms carbonic acid, which lowers the pH of seawater, and may have an adverse effect on oceanic biota. To circumvent these problems, the UML researchers proposed to inject into the ocean not pure liquid CO_2, but an emulsion of CO_2 in water stabilized by limestone ($CaCO_3$) particles. The emulsion is heavier than seawater, hence it will sink deeper from the injection point rather than buoy upward. Secondly, the $CaCO_3$ coated CO_2 droplets will not acidify the seawater. In the first year of the NETL sponsored contract, the UML researchers found that, under proper conditions, liquid CO_2 will form an emulsion in water in the presence of powdered limestone in which the globules of CO_2 are denser than water. In the second year of the contractual period the UML researchers would like to optimize the conditions for globule formation, including CO_2 to $CaCO_3$ ratio, and $CaCO_3$ particle size, as well as globule stability over long periods. In the third year extension of the contract, the effect of impurities and ion strength on globule formation will be investigated, as well as the possibility of using other particles than $CaCO_3$ for globule formation, including fly ash and various minerals. The stability of globules will also be investigated in the NETL water tunnel facility at PETC. Data collected during this phase will facilitate the development of modeling for future scaleup work.

The high pressure batch reactor in which CO_2-in-water emulsions are formed stabilized by powdered limestone particles.

Primary Project Goal

The general objective of this work is to establish a database to enable the evaluation of an improved process for the deep water ocean sequestration of CO_2. The process forms globules of liquid CO_2 in water, with the globules being stabilized by particles of limestone at the CO_2/water interface.

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Heino Beckert
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-4132
heino.beckert@netl.doe.gov

Dan S. Golomb, PhD
Professor Emeritus
Department of Environmental, Earth, and Atmospheric Sciences
University of Massachusetts Lowell
Lowell, MA 01854
978-934-2274
978-934-3069 fax
dan_golomb@uml.edu

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

University of
Massachusetts Lowell

COST

Total Project Value
$577,518

DOE/Non-DOE Share
$481,551 / $95,967

Benefits

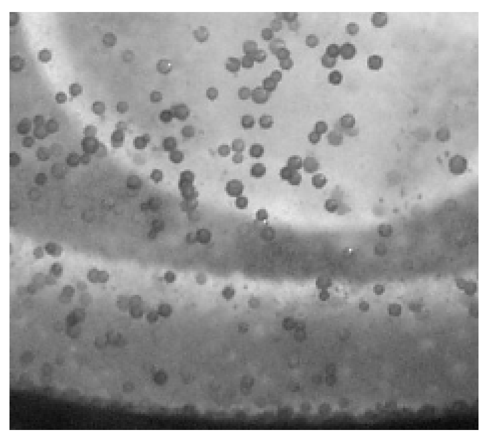
Concerns about the contribution of greenhouse gas emissions to global warming have led to the study of ways to capture and sequester CO_2 at major emitting sources (e.g. fossil fueled power plants and industrial boilers) to prevent its emission into the atmosphere. One potential sink for CO_2 are the oceans of the world, with almost unlimited capacity to sequester CO_2. However, dissolving CO_2 in seawater lowers its pH, which may have adverse effects on aquatic organisms. If this project is successful, it could provide a method for ocean sequestration of CO_2 that would avoid this problem, thus making it possible to continue the use of cheap and abundant coal and other fossil fuels until other non-CO_2 emitting energy sources become available.

Objectives

- To construct a batch high-pressure reactor in which CO_2, water, and finely ground limestone will be mixed at elevated pressure.
- To analyze emulsions in-situ using light microscopy and light scattering to determine their structural properties, the size of the droplets and $CaCO_3$ particles that stabilize the emulsions, hydrate formation, and other significant properties.
- To vary initial conditions (pressure, temperature, ingredients, water type, particle size, etc.) to determine the effects on emulsion physical and chemical characteristics.
- After successful completion of batch experiments, to convert the reactor into a flow system in which liquid CO_2 and pulverized limestone can be fed continuously and thoroughly mixed to form an emulsion.
- To use the flow system to investigate the physical and chemical characteristics of the emulsions as a function of time while varying initial conditions.
- To analyze the data to report findings on observed relationships between measured characteristics and operating conditions.
- To perform a simple economic analysis of the costs associated with the process, which will reflect the amounts and costs of raw materials (limestone or other particles) and the energy required to pulverize, mix and transport the emulsion to the deep ocean, expressed as the cost of sequestering one ton of CO_2 in the ocean.

Accomplishments

A high-pressure batch reactor with a view window has been constructed. This reactor was used to conduct a wide range of tests using various proportions of liquid CO_2, water, and pulverized limestone to form emulsions of CO_2 droplets in water stabilized by $CaCO_3$ particles. After thorough mixing of the ingredients, a stable emulsion forms with globules consisting of an inner core of liquid CO_2 coated with a sheath of $CaCO_3$ particles dispersed in water. Using limestone particles with a size range of 6-13 ìm and the proper stirring conditions, globules with diameters of 100-200 ìm were formed which were denser than water and sank to the bottom of the high pressure reactor. The globules were observed for many hours and appear to be stable. Furthermore, the water in the reactor had a pH in the range of 7-10 compared to a pH of 3-4 for carbonic acid. It was also demonstrated that artificial seawater (3.5% NaCl solution) can be used instead of deionized water to form a stable emulsion. It has been estimated that about 0.5 to 0.75 tons of pulverized limestone is required per ton of CO_2 for stable emulsion formation. The construction of the flow reactor has been commenced in which the conditions for stable emulsion formation can be further studied, and the long time stability of the formed globules can be investigated.



A close-up view of the CO_2 globules coated with a sheath of limestone particles. Globules are settling out of suspension.

Proj289.pmd

PROJECT facts

Sequestration

04/2003

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

ENHANCEMENT OF TERRESTRIAL CARBON SINKS THROUGH RECLAMATION OF ABANDONED MINE LANDS IN THE APPALACHIANS

Background

The continuing demand for fossil-fuel-based power and the associated rise in atmospheric carbon dioxide (CO_2) concentration will require the development of innovative ways to capture and store carbon. Terrestrial ecosystems, including both soil and the related vegetation, are recognized as significant biological CO_2 "scrubbers" and are major sinks for removing CO_2 from the atmosphere. Since reclaimed mined lands are essentially devoid of soil carbon, these areas provide an excellent opportunity to sequester carbon in both soils and vegetation.

Much of the strip mining in the Eastern U.S. is on forested lands. Unfortunately, after mining, most of these areas are restored as grasslands. However, much more carbon is stored in a hectare of forest than in a hectare of grasslands. Stephen F. Austin State University (SFASU) is studying the CO_2 sequestration potential resulting from afforestation of abandoned mined lands using Northern red oak. Within the Appalachian coal region, there may be up to 400,000 hectares of abandoned mined lands. These areas contain little or no vegetation, provide little wildlife habitat, and may pollute streams. Reclamation and afforestation of these sites has the potential to sequester large quantities of carbon in terrestrial ecosystems. Utility companies with high CO_2 emissions are interested in mitigating these emissions through the use of carbon credits. In order to establish a carbon credit market and claim carbon credits, utility companies need to partner with landowners who do not currently have forests on their land. Abandoned mined lands in Appalachia should offer excellent sites for such partnerships.

Primary Project Goal

The overall goal of this project is to sequester carbon in abandoned mine lands. This project will determine how to increase carbon sequestration in forests while increasing forest yields and providing other desirable ecosystem benefits.

Objectives

- To determine the profitability of forest management in the Appalachian region when only timber is considered and when both timber and carbon credits are considered.
- To determine optimal forest management schedules using Forest Management Optimizer (FORMOP).
- To determine the amount of carbon that can be sequestered on abandoned mined lands.

CONTACT POINTS

Scott M. Klara
Sequestration Product Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

John Litynski
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-1339
john.litynski@netl.doe.gov

Gary D. Kronrad
Arthur Temple College of Forestry
Stephen F. Austin State University
SFA Station
P.O. Box 13024
Nacogdoches, TX 75962
gkondrad@sfasu.edu

CUSTOMER SERVICE

800-553-7681

WEBSITE

www.netl.doe.gov

Enhancement of Terrestrial Carbon Sinks Through Reclamation of Abandoned Mine Lands in the Appalachians

PARTNERS

Stephen F. Austin State University

Texas Utilities Electric Company

USDA Forest Service

TOTAL ESTIMATED COST

Total Project Value	$839,504
DOE	$628,169
Non-DOE Share	$211,335

Accomplishments

FORMOP, a combination of the U.S.D.A. Forest Service's growth and yield models and dynamic and economic programs, was used to simulate tree growth as a function of variables such as site quality, thinning frequency and intensity, and rotation length. Results indicate that costs of sequestering carbon in Northern red oak stands on West Virginia abandoned mined lands range from $7.20-40.50/tonne. These numbers reflect the cost of carbon sequestration without considering profits from timber management. When the timber revenues are taken into consideration, the net revenue earned from the reforestation of these lands ranges from a profit of approximately $34/tonne of carbon to a loss of $40/tonne. The market price of carbon credits will determine the attractiveness of sequestration projects on these poorer quality mined lands.

Benefits

Mine reclamation, afforestation and forest management can provide two major benefits. The first is financial. Growing forests can generate revenue, create jobs, and enhance local economies. The second is environmental. Afforestation can reduce the negative effects of global warming by storing carbon in trees, enhance wildlife habitat, improve air and water quality, reduce soil erosion, and increase recreational opportunities.

Figure 1. Approximately 1.6 million acres of land in the United States supports only limited vegetation due to past and present mining operations.

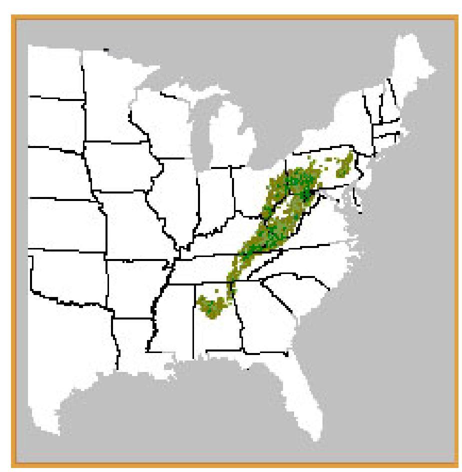


Figure 2. Abandoned Mine Lands in Appalachia

Proj230.pmd

PROJECT facts

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

Sequestration

07/2004

RESTORING SUSTAINABLE FORESTS ON APPALACHIAN MINED LANDS FOR WOOD PRODUCTS, RENEWABLE ENERGY, CARBON SEQUESTRATION, AND OTHER ECOSYSTEM SERVICES

Background

Over 1.8 million hectares of land nationally (including 1.1 million hectares in the east) were under active coal mining permits during 2001; of these lands, over 600,000 hectares (including 200,000 hectares in the east) are currently classified as "disturbed." Converting these abandoned lands to productive forests has the potential of sequestering 100 million metric tons of carbon.

Virginia Polytechnic Institute and State University is working to develop hardwood and conifer forests on eastern U.S. coalfields, not only to sequester carbon but also to support a wood products economy, help control flooding, and provide clean water, wildlife habitat, biodiversity, and recreation. Current mining practices remove and burn the carbon-rich forest. Then, following coal removal, many eastern U.S. mine sites are reclaimed to grass having one-fifth the potential for carbon sequestration compared to reforestation. Primary studies indicate that through optimal reclamation/restoration procedure, there is a potential for mined-land forests to capture 250 to 290 tonnes of carbon per ha over a period of 70 years, at which time the mined lands' biological potential is nearly restored.

Primary Project Goal

The primary goal of this project is to determine the biological and economic feasibility of restoring high-quality forests on mined land and to measure carbon sequestration and wood production benefits achieved with restored forests.

Objectives

- To demonstrate and verify large-scale carbon sequestration by reforestation of mined lands using high-value tree species.
- To develop a forest site classification and mapping system for reclaimed mined sites.

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

John Litynski
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-1339
john.litynski@netl.doe.gov

James A. Burger
Virginia Polytechnic Institute and State University
Blacksburg, VA 24062
540-231-2680
jaburger@vt.edu

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

Restoring Sustainable Forests on Appalachian Mined Lands for Wood Products, Renewable Energy, Carbon Sequestration, and Other Ecosystem Services

PROJECT PARTNERS

Virginia Polytechnic Institute and State University

Mead-Westvaco

Plum Creek Timber

Mountain Forest Products

COST

Total Project Value:	$629,381
DOE:	$494,400
Non-DOE Share:	$134,981

- To complete a cost benefit analysis of reforestation on these lands.
- To quantify the social and ecological benefits derived from these projects.

Accomplishments

Preliminary criteria for classifying the quality of mined lands have been developed. Also, a preliminary economic analysis of the feasibility of reforestation with several different forest types and levels of management, have been completed. Future efforts will be aimed at looking into regulatory factors that can achieve the ultimate goal with reforestation of high quality forests for carbon sequestration and other eco-assets. Three test sites (one each in West Virginia, Ohio, and Virginia) have been identified to test reforestation practices on mined lands.

Benefits

This study will provide estimates of the carbon sequestration potential for mined lands of varying quality using various reforestation methods. It will provide an inventory of mined lands available for reforestation, an estimate of cost-per-ton of carbon sequestered by reforestation on mined lands, and an estimate of the total eastern-U.S. mined-land carbon-sequestration potential under various policy-incentive scenarios. It will also determine the social and ecological benefits associated with the reforestation of these mined lands.

PROJECT facts

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

Sequestration

07/2004

CARBON SEQUESTRATION ON SURFACE MINE LANDS

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

John Litynski
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-1339
john.litynski@netl.doe.gov

Donald H. Graves
University of Kentucky
106 T.P. Copper Building
Lexington, KY 40546-0073
859-257-2906
dgraves@ca.uky.edu

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

Background

Large quantities of carbon dioxide (CO_2) are being emitted to the atmosphere by fossil-fuel combustion and other activities. Scientific observations have indicated that atmospheric CO_2 concentrations are steadily rising, which may negatively impact global climate and, consequently, affect the environment and economy of the U.S. Researchers around the globe are addressing methods by which we can reduce atmospheric concentrations of CO_2. One way to offset CO_2 emissions is through enhanced sequestration of carbon in terrestrial systems. Land management practices designed to increase terrestrial carbon inventories include both improving present land use, as well as conversion of land to other uses. Abandoned and previously reclaimed mine lands in the Appalachian region may provide excellent sites for enhanced terrestrial carbon sequestration through reforestation. Since these areas are essentially devoid of carbon after mining, the planting of forests can dramatically affect carbon uptake on these sites, thus increasing carbon accumulation in soils and forest biomass.

To demonstrate the potential for terrestrial carbon sequestration on mined lands, the University of Kentucky, with the U.S. Forest Service, has initiated a reforestation project at several locations within Kentucky. These sites differ with respect to geology and reclamation practices. In this study, various methods are being employed to decrease both physical and chemical limitations on plant growth so that the establishment of high value forest species (hardwood and conifers) is possible.

Primary Project Goal

The primary goal is to establish planting sites to demonstrate low compaction surface mine reclamation techniques for carbon sequestration through the growth and harvesting of high value trees.

Objectives

- To develop concepts that combine indirect capture and storage of CO_2 with concomitant reduction of criteria-pollutant emissions and improved water quality.
- To demonstrate and verify large scale carbon sequestration by reforestation of post-mining lands using high value tree species.

Carbon Sequestration on Surface Mine Lands

PROJECT PARTNERS

University of Kentucky

COST

Total Project Value:	$1,268,542
DOE:	$1,000,000
Non-DOE Share:	$ 268,542

Accomplishments

- Planting sites were identified at three mines in three widely separated locations.
- Over 60 ha of seedlings (>100,000) have been planted thus far with an additional 120 ha remaining for years two through three of the project.
- More detailed studies to address specific questions pertaining to carbon flux are being initiated.

Benefits

The results of this study will not only enhance our understanding of carbon cycling in mined lands but also add to the knowledge base from which specialists draw when planning future reclamations. Considering the potential for mine lands to sequester carbon to offset rising levels of CO_2 in the atmosphere, the results will help justify a change in current mine reclamation practices and perceptions to allow loose dumped material which encourages forest establishment.

Tree growth on a mine site

Proj235.pmd

U.S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

10/2002

CARBON CAPTURE AND WATER EMISSIONS TREATMENT SYSTEM (CCWESTRS) AT FOSSIL-FUELED ELECTRIC GENERATING PLANTS

Background

A 100-acre reclaimed surface mine area at the 2,558-megawatt Tennessee Valley Authority (TVA)-owned Paradise Fossil Plant near Drakesboro, Kentucky, is serving as the demonstration site where by-products from the plant's wet scrubber will be used to amend the soils. Wastewater from the flue gas desulfurization process that targets SO_2 control and selective catalytic reduction for NO_X control will be used to irrigate the trees and herbaceous cover. The plants will in turn capture and store carbon dioxide while reducing pollutant loadings to the local watershed.

The "Carbon Capture and Water Emissions Treatment System" (CCWESTRS) will be constructed at the Paradise Fossil Plant on existing, poorly reclaimed coal mined land by establishing plantings of vegetative species. Sequestration will occur through carbon uptake by trees, with biomass recovery for the forest products industry, and in the soil, which currently has low carbon levels. An average of 1.5 to 3 tons of carbon per acre/year is estimated to be sequestered in the CCWESTRS over a 20-year period.

The Tennessee Valley Authority will design and install a system to drip irrigate Flue Gas Desulfurization (FGD) wastewater over the entire site. Tree growth and response, along with other relevant observations will be performed over the course of the project through 2003 to determine effectiveness of the integrated technologies to sequester carbon and accomplish other project benefits.

PRIMARY PROJECT PARTNERS

National Energy Technology Laboratory

Tennessee Valley Authority

Electric Power Research Institute

CUSTOMER SERVICE

800-553-7681

WEBSITE

www.netl.doe.gov

NETL

Carbon Capture and Water Emissions Treatment System (CCWESTRS) at Fossil-Fueled Electric Generating Plants

CONTACT POINTS

John T. Litynski
Terrestrial Sequestration Program Coordinator
National Energy Technology Laboratory
P.O. Box 880
3610 Collins Ferry Road
Morgantown, WV 26507-0880
304-285-1339
john.litynski@netl.doe.gov

Scott M. Klara
Sequestration Product Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

The FGD water poses the major obstacle for the project. Toxic in most respects and requiring treatment before its ultimate discharge into the Green River, the FGD water contains certain boron compounds, which hinder growth and survival of trees and other plants at concentrations above 2-4 mg/l. The Paradise FGD water has over ten times that concentration.

Flue Gas Desulfurization wastewater pond

Primary Project Goal

To demonstrate a "whole plant" approach using by-products from a coal-fired power plant to sequester carbon in an easily quantifiable and verifiable form.

Objectives

- Provide economically competitive and environmentally safe options to offset projected growth in U.S. baseline emissions of greenhouse gases after 2010
- Achieve the long-term goal of $10/ton of avoided net costs for carbon sequestration
- Provide half of the required reductions in global greenhouse gases by 2025

Benefits

- Developing a potentially widely applicable passive technology for water treatment for criteria pollutant release reductions
- Using power plant by-products to improve coal mine land reclamation and carbon sequestration
- Developing wildlife habitat and green-space
- Generating Total Maximum Daily Load (TMDL) credits for water and airborne nitrogen
- Developing additional forest lands that will be available for timber harvesting

Proj134.pmd

*Factsheet Under Development

Exploratory Measurements of Hydrate and Gas Compositions*
-LLNL

Page left blank to accommodate 2-sided printing

***Factsheet Under Development**

Enhanced Practical Photosynthesis Carbon Sequestration*
-ORNL

Page left blank to accommodate 2-sided printing

PROJECT facts

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

Sequestration

04/2004

Enhancing Carbon Sequestration and Reclamation of Degraded Lands with Fossil-Fuel Combustion By-Products

Background

The concentration of CO_2 in the atmospheric has increased about 30% during the past 200 years. The increase, which is expected to continue throughout the foreseeable future, is largely driven by fossil fuel combustion; although, prior to 1940, human land use activities and land use changes made a significant contribution. The CO_2 rise and concomitant climatic changes might be slowed if CO_2 could be transferred from the atmosphere to terrestrial ecosystems and stored there for significant periods. Long-term storage of atmospheric carbon (C) in terrestrial ecosystems (terrestrial C sequestration) can potentially be achieved by enhancing natural biological processes that assimilate CO_2 (photosynthesis) and add the assimilated C to long-lived plant tissues, such as wood, and soil organic matter. Thus, to slow the increase in atmospheric CO_2 and other greenhouse gases and thereby minimize their potential environmental and economic consequences, a program of C sequestration may be required.

Reclamation of degraded and disturbed lands, such as mine spoil materials, highway rights-of-way, and poorly managed lands, through the addition of beneficiating amendments has a long history of research, but there are new factors to consider, since the need for C sequestration may change the economics. In the U.S., approximately 1% of the surface area consists of mined lands or highway rights-of-way. Poorly managed lands account for another 15%. Over the next 50 years, an increase of 1 wt% in stored-C content on these lands could remove on the order of 12 billion tons of C, a significant fraction of the total needed to stabilize atmospheric CO_2 levels.

Degraded lands are often characterized by acidic pH, low levels of key nutrients, compaction, poor soil structure, and limited moisture retention capacity. Addition of energy-related by-products can address these adverse conditions. The potential of energy by-products as soil amendments to enhance C sequestration in degraded lands can be most fully realized if these inorganic by-products are applied in conjunction with organic amendments, including mulch from biomass production and process wastes,

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

John Litynski
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-1339
john.litynski@netl.doe.gov

Primary Project Goal

The overall goal is to study the use of fossil fuel by-products to foster carbon sequestration in degraded lands. This has the triple benefits of carbon storage, by-product utilization, and land reclamation.

such as biosolids and pulp and sludge from paper production. These organic amendments can complement and extend the benefits of fly ash and other inorganic by-products. Thus, the addition of a suite of amendments containing both organic and inorganic by-products offers great potential for improving degraded land, increasing the sequestration of C, and utilizing energy by-products.

Conventional techniques for measuring carbon content in soil may not be cost-effective for sequestration projects. Thus, the soil carbon analysis of the numerous samples that may be required to characterize changes in soil carbon for sequestration projects could be very expensive. This project is examining the use of a laser spectroscopic technique for carbon and nitrogen analysis. Its real-time monitoring capabilities, high degree of analytical sensitivity and selectivity, and potential use in the field make it a good candidate.

Objectives

- To examine the terrestrial carbon sequestration potential of lands that have been disturbed by mining, highway construction, or poor management practices.
- To identify the sequestration-enhancing effects of land amendment by a combination of solid by-products from fossil-fuel combustion and biological wastes from treatment facilities.
- To identify optimal selection and delivery strategies to maximize the contribution of amendments to carbon sequestration.
- To evaluate existing experimental sites, conduct laboratory experiments to identify key amendment types and potential management strategies, and design field experiments to test and demonstrate carbon sequestration.
- To foster interaction between the scientific and user communities to maximize the application of the new knowledge generated by this project.

Accomplishments

Alkaline fly ash amendments have been identified as having a significant ability to enhance humification, the main process responsible for organic carbon sequestration in soils. The fly ash properties contributing to this effect are believed to include alkalinity, porosity, and the presence of unburned carbon, which acts as a hydrophobic sorbent for organic compounds. The laboratory results are consistent with field studies indicating that after 15 - 30 years lands amended with fly ash have higher levels of carbon in the soil and that amendment with biosolids does not produce a consistent benefit. Further study of the role of unburned carbon may allow productive use of alkaline fly ash from low-NOx burners that is currently relegated to landfills. Work will involve characterization of fly ash with respect to alkalinity, micro- and meso-porosity, and unburned carbon content and testing to determine efficacy in promoting humification. Tests involving soils with and without carbonate minerals will be performed to confirm the minimization of carbonate dissolution by the presence of unburned carbon. This work will complement studies of the same ashes at ORNL with respect to their potential for nitrous oxide emissions and leaching of metals. Current results indicate very low potential for leaching of metals and no toxicity of the leachates when measured using the Microtox technique. Also, mixing fly ash with biosolids alters leaching but the biosolids can act as a source of metals for leaching. Project results will be summarized in a set of optimum site-management practices and practical guidelines that include policy, stakeholder, and technical considerations.

Soil sampling pit showing development of soil over coal refuse.

CONTACT POINTS (continued)

Anthony Palumbo
ORNL
1 Bethel Valley Road
P.O. Box 2008
Oak Ridge, TN 37830
865-576-8002

James E. Amonette
PNNL
902 Battelle Boulevard
P.O. Box 999
Richland, WA 99352
509-376-5565

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

Oak Ridge National Laboratory (ORNL)

Pacific Northwest National Laboratory (PNNL)

Virginia Polytechnic and State University

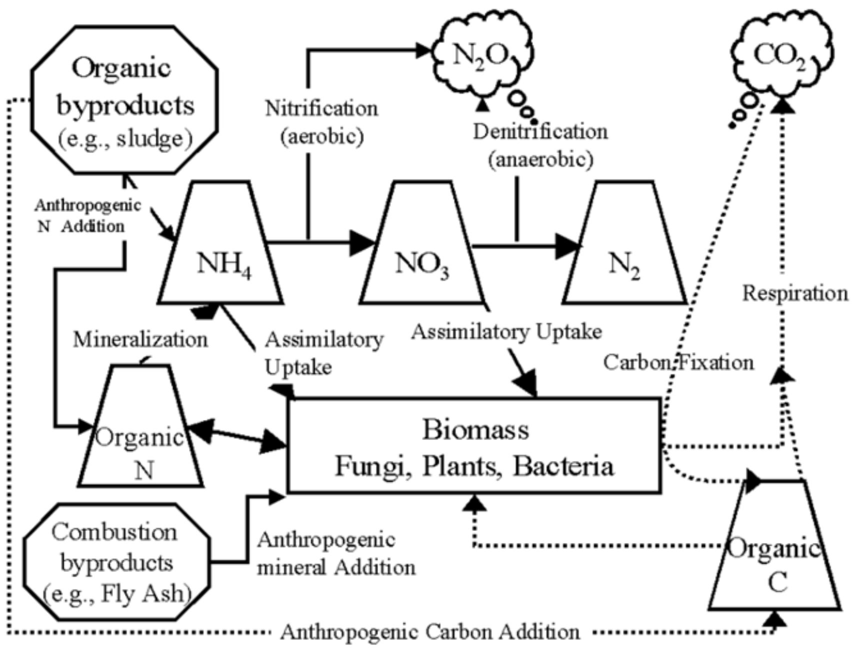
COST

Total Project Value
$1,152,000

DOE/Non-DOE Share
$1,152,000/$0

Benefits

This project has the potential for triple benefits. First, by increasing the carbon content of soils, it will decrease the net emission of CO_2 to the atmosphere. Second, it provides a beneficial use of waste products that currently must be landfilled at a cost. Third, marginal lands are brought back into productive use as forests, pastures, agricultural lands or recreational areas.



Proj288.pmd

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

Sequestration

08/2002

An Investigation of Gas/Water/Rock Interactions & Chemistry

Background

About two thirds of the United States is underlaid by deep saline aquifers that have an estimated CO_2 adsorption capacity of between 320 to 10,000 billion tons. Unfortunately, there are a large number of uncertainties associated with the heterogeneous reactions which may occur between CO_2, the brine, and minerals in the surrounding strata—especially with respect to reaction kinetics. This project focuses on the complex solution and surface chemistry of CO_2 in brines in the presence of host rock and the special types of analyses required to study the reaction kinetics. Carbonate mineral formation/dissolution reactions that may be important in geologic sequestration in deep saline aquifers will be identified. The kinetics of CO_2 dissolution in the liquid phase and subsequent substrate-water reactions are slow and poorly understood. Understanding the kinetics of both these types of reactions and the processes controlling them is essential to understanding the conversion of CO_2 into stable carbonate minerals.

A compilation of existing brine data from a variety of sources, and a complete statistical analysis of the brine chemistry and other geological parameters associated with brine aquifers would be a valuable tool for both experimental and modeling studies of CO_2 sequestration in brines. Currently, NETL is developing a brine database that includes temperature, depth, pressure, and a variety of chemical variables (pH, sodium, iron, chloride, bicarbonate, calcium, magnesium, sulfate, and total dissolved solids) on some 64,000 brines taken from the contiguous United States. Sources of these data include those provided by the USGS, searches of geoscience literature, State Geological Surveys and oil and gas producing companies. Additionally, NETL has instituted a limited field program of brine collection throughout the United States. This brine sampling is being done in conjunction with other government agencies and oil and gas companies.

Primary Project Goal

The ultimate objective of the work being performed jointly at NETL and the United States Geological Survey is to carry out an experimental study to assess the role of the chemistry of formation water in CO_2 solubility. Then the role of rock mineralogy in determining the potential for CO_2 sequestration through geochemical reactions will be assessed.

Objectives

- Investigate kinetics of CO_2 dissolution in brines at temperatures and pressures appropriate for deep saline aquifer carbon dioxide sequestration.
- Improve the understanding of the processes by which mineral carbonates are formed and study the reactivity of various mineral substrates involved in these processes.
- Assess and collect both brines and surrounding geologic strata in selected brine formations in the conterminous United States in order to determine their potential to sequester CO_2 from fossil fuel fired power plants.

PRIMARY PARTNERS

National Energy Technology Laboratory
United States Geological Survey
Parsons Power
Battelle Memorial Institute
University of Pittsburgh
California University of Pennsylvania
University of Texas
Case Western Reserve University

DOE FUNDING PROFILE

Prior FY's	$682,000
FY2002	$817,000
Future FY	TBA

TOTAL ESTIMATED COST

DOE	$1,499,000

CUSTOMER SERVICE

800-553-7681

WEBSITE

www.netl.doe.gov

An Investigation of Gas/Water/Rock Interactions & Chemistry

- Develop reservoir or basin scale models that include flow, mass transport, and chemical reaction processes for CO_2 injection and field pilot test sites.

Accomplishments

The facilities to conduct hydrothermal CO_2-water-rock reactions and analyze these complex mixtures have been developed at NETL. Work on the systematic study of the solubility of CO_2 in increasingly complex salt solutions is currently underway.

In addition to construction of a database containing physical and chemical information on over 64,000 brine wells, NETL has added information on the locations of coal-fired power plants and information on seismic activity. A composite map depicting the power plants, saline formations, and seismic potential was constructed. The high-pressure chemistry of CO_2 with brines sampled around the nation has been started. The pertinent reactions have been identified and the effect of temperature, pressure, pH, and other variables determined. Lastly, several simulations of brine field sequestration have been developed. These include development of sophisticated reservoir models as well as reactive transport models.

Benefits

This project will provide useful information in the area of reaction kinetics dealing with carbon dioxide and surrounding minerals and also provide a compiled brine database of some 64,000 brine wells in the United States. By compiling a database of these brines along with power plants and seismic activity in the United States, a more efficient means of storage can take place in optimal locations. Taking nearby power plant emissions and local seismic activity into consideration, researchers and engineers become more informed as to where precautions need to be taken or simply where areas of higher risk are located. Thus, an understanding of the fundamental chemistry associated with the reactions coupled with a detailed brine database provides much needed information and efficiency to the actual sequestration projects. Additionally, by capturing carbon dioxide and sequestering it, harmful emissions into the atmosphere are prevented that may further increase global warming.

CONTACT POINTS

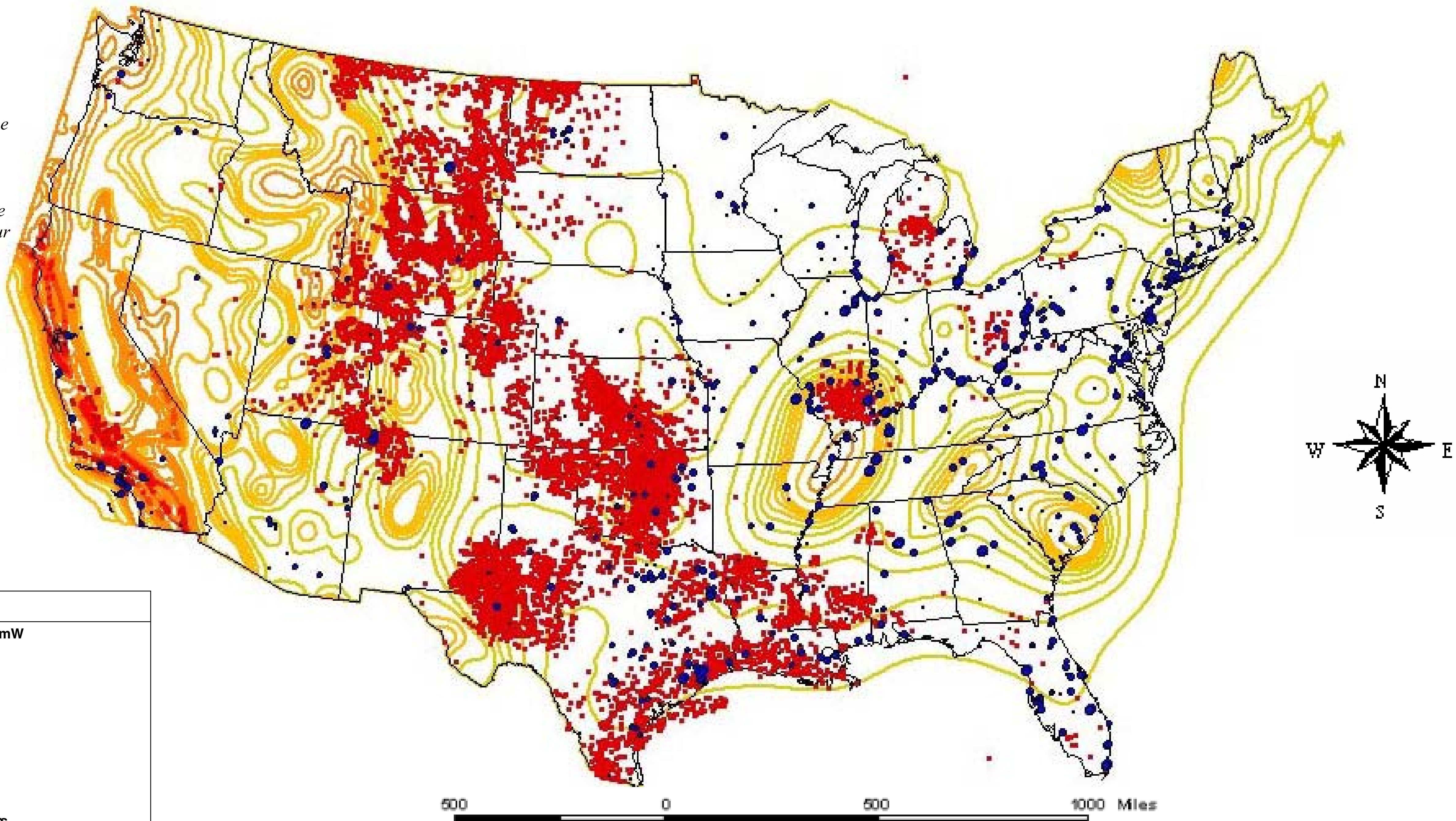
Curt White
Carbon Sequestration Science Focus Area Leader
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-5808
curt.white@netl.doe.gov

Proj187.pmd

GEOLOGIC SEQUESTRATION OF CARBON DIOXIDE

Powerplant Locations • Brine Well Locations • Seismic Potential

The black circles on the map indicate the location of the fossil fuel fired power plants. The size of the black circles is proportional to the megawattage of the power plant. The gray areas indicate the location of brine wells, while the contour lines indicate seismic potential.



LEGEND

Power Plants Nameplate Capacity >= 100mW

- 100 - 420 MW
- 421 - 875 MW
- 876 - 1469 MW
- 1470 - 2242 MW
- 2243 - 3969 MW

US States

US Counties

Brine Wells

Peak Ground Acceleration,
10% Probability of Exceedance in 50 years

0 - 6 ft/sec/sec	Albers Equal Area Projection
7 - 15 ft/sec/sec	Clarke 1866 Spheriod
16 - 40 ft/sec/sec	Central Meridian -96.0
41 - 60 ft/sec/sec	Reference Latitude 37.5
61 - 100 ft/sec/sec	2nd Standard Parallel 45.5

Power generation data derived from EPA Emission and Generation Resource Database 1998 (E-GRID98) and DOE/EIA 767.
Geological coverages derived from data set generated under DOE/NETL contract by the University of Texas, Bureau of Economic Geology

**** DRAFT by Garret Veloski DRAFT ****

PROJECT facts

U.S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

Sequestration

08/2002

PHYSICS AND CHEMISTRY OF COAL-SEAM CO_2 SEQUESTRATION & COALBED METHANE PRODUCTION

Background

Recently, the concept and practice of carbon management via the sequestration of carbon dioxide by coal seams and the concurrent production of coalbed methane (CBM) have increased in potential significance. The injection of CO_2 into deep, unmineable, gassy coal seams may substantially increase CH_4 (methane) production above the level achievable by standard depressurization methods. Water continues to play a key role in CBM production, yet explanations in the coal literature of how water does this on a molecular scale are presently undeveloped. Thus, a fundamental understanding of the mechanism(s) by which sorbed water influences, or can influence, coalbed methane production, with and without CO_2 sequestration is necessary.

Additionally, research is being conducted to obtain information useful for assessing the technical feasibility of CO_2 sequestration in coal-seams. Areas of interest include estimation of the capacity of a coal-seam to adsorb CO_2 (*adsorption isotherm*), the validity of inter-lab comparisons of isotherm data (*inter-lab precision*), and the stability of the CO_2 saturated phase once formed—especially with respect to how it might be affected by changes in the post-sequestration environment (*environmental effects*). The affects of temperature, pressure, and coal rank on the ability of coal to adsorb CO_2 have been investigated.

Primary Project Goal

The goals of the research are to ultimately provide guidelines for drilling of new CBM production wells and enable field engineers to determine if cases of poor CO_2 sequestration and/or low methane productivity can be attributed to non-ideal coalbed temperatures/depths or, perhaps, to other factors.

Objectives

- Determine the temperature dependence of CO_2 sequestration and methane production.
- Determine adsorption isotherms for pure gases in a static system for coals of NETL interest.
- Develop a flow system to generate adsorption isotherms via numerical techniques established for data analysis.

PRIMARY PARTNERS

National Energy Technology Laboratory
Pennsylvania State University
University of Pittsburgh
University of Oklahoma
University of Southern Illinois
CSIRO
Netherlands Institute of Applied Geoscience TNO
Illinois State Geological Survey

DOE FUNDING PROFILE

Prior FY's	$257,000
FY2002	$441,207
Future FY	TBA

TOTAL ESTIMATED COST

DOE	$698,207

CUSTOMER SERVICE

800-553-7681

WEBSITE

www.netl.doe.gov

NETL

PHYSICS AND CHEMISTRY OF COAL-SEAM CO_2 SEQUESTRATION & COALBED METHANE PRODUCTION

CONTACT POINTS

Curt White
Carbon Sequestration Science Focus Area Leader
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-5808
curt.white@netl.doe.gov

Accomplishments

Advanced CO_2/CH_4 Concepts (CO_2 sequestration & CBM production):
A method for simultaneously accounting for heats of CO_2 and CH_4 sorption/desorption, moles of CO_2 and CH_4 sorbed/desorbed, extents of dehydration, and sample temperature was developed and a manuscript was prepared and accepted for presentation at various conferences. Mathematical methods for resolving complex calorimetric thermograms were developed. Accordingly, an apparent correlation between hypothetical extents of coal dehydration and predicted relative viscosities of water in the narrow capillaries, mesopores, and micropores of coal was discovered.

CO_2 Sorption, Transport, & Environmental Chemistry (CO_2 Sequestration):
A static system for the measurement of adsorption isotherms was assembled, pressure-tested, and successfully employed to generate data along with a derived equation used to separate the actual surface adsorption from the effects of coal swelling on the isotherm shape. The extent of actual physical adsorption was determined, the heats of adsorption were calculated, and the values were found to agree within 10% of each other. NETL has developed a new theory that allows one to obtain information on coal swelling from the experimentally derived adsorption isotherm.

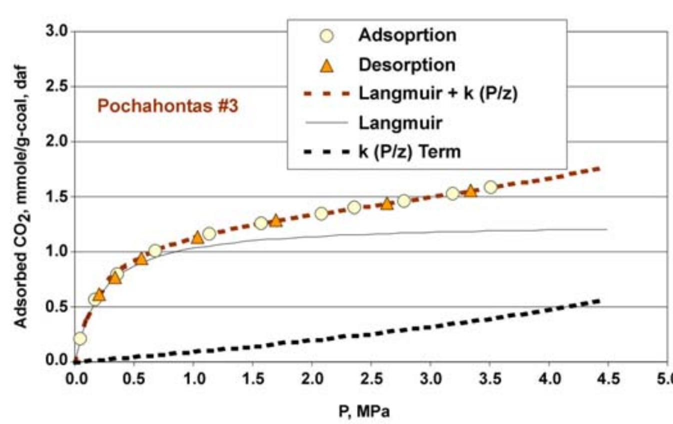
Benefits

This project will provide guidelines for both efficient sequestration of carbon dioxide in coal seams and enhanced methane production. Through an understanding of the fundamental chemistry involved in the CO_2 adsorption/CH_4 desorption process, it will be possible to select optimum conditions for CO_2-enhanced coalbed methane production/sequestration. The project has resulted in development of a new theory of coal swelling and how the CO_2 adsorption process affects swelling. The new theory allows one to obtain information on coal swelling from simple adsorption isotherm measurements. The enhanced methane production associated with CO_2 sequestration will help to defray sequestration costs. Additionally, by capturing carbon dioxide and sequestering it, harmful emissions into the atmosphere are prevented that may further increase global warming.

NETL's New Theory on Coal Swelling

Adsorption Isotherms Appear to Be Combinations of a **Surface Adsorption Term** and a **Constant Term**

$$n_{\text{exp}} = n_{ads} + k(P/z)$$



Proj186.pmd

PROJECT facts

U.S. Department of Energy
National Energy Technology Laboratory

Sequestration

08/2002

Oceanic Sequestration

Background

Stabilization of rising levels of atmospheric greenhouse, primarily CO_2, may require the use of non-atmospheric carbon sequestration options in addition to maximizing improvements in energy conversion, end-use efficiencies, and fuel switching to lower-carbon or carbon-free energy sources. One potential large-scale sequestration option is to directly inject CO_2 into the ocean at depths greater than 1500m where it should be effectively sequestered for hundreds of years or longer. Generally, the deeper the CO_2 can be deposited, the longer the residence time in the ocean.

The current effort is directed at determining the fate of CO_2 introduced into the deep ocean and how the icelike CO_2 hydrate impacts the process. The experimental work is carried out in two facilities: a High-Pressure, Variable-Volume View-Cell (HVVC) and a High-Pressure Water Tunnel Facility (HTWF). In addition, a Low-Pressure Water Tunnel Facility (LWTF) capable of being chilled has been constructed and used to test various configurations of flow conditioners and section divergence angle and length.

Primary Project Goal

The objectives of the research are to obtain information useful both for assessing the technical feasibility of oceanic CO_2 sequestration and for developing optimal methods of introducing the CO_2 into the ocean.

Objectives

- Determine hydrate formation and dissolution conditions as a function of dissolved CO_2 content, temperature, and pressure, especially at higher levels of dissolved CO_2.
- Characterize the flow patterns possible in the water tunnel test sections and develop predictive tools for designing the internal geometries necessary for optimum stability of CO_2 (or any fluid particle) over an anticipated range of simulated ocean depths.
- Initiate CO_2 drop injection experiments in the HWTF to investigate depth of injection and initial dissolved CO_2 content effects on the fate of $CO_{2.}$

PRIMARY PARTNERS

National Energy Technology Laboratory

University of Pittsburgh

DOE FUNDING PROFILE

Prior FY's	$ 0
FY2002	$ 475,000
Future FY	TBA

TOTAL ESTIMATED COST

DOE	$ 475,000

CUSTOMER SERVICE

800-553-7681

WEBSITE

www.netl.doe.gov

NETL

Oceanic Sequestration

Accomplishments

A theoretical model that predicts formation conditions for CO_2 and other hydrate-forming gases was developed during FY2001 along with an initial set of experiments used to validate this model. Results show that under conditions of temperature and pressure planned for deep-ocean sequestration, the formation of hydrate from dissolved CO_2 may be in areas of elevated dissolved CO_2 concentration, such as near the injection site.

High-Pressure Water Tunnel Facility in newly renovated laboratory

The flow conditioning elements were tested in the LWTF to determine the design parameters needed for stabilization of a CO_2 fluid particle in the HWTF over the range of anticipated ocean injection conditions. The precision of the measurements was improved and now the entire procedure can operate without intervention and automatically collects sets of profiles for different flow rates. Additionally, a full 3-D finite element analysis of the flow through the conditioner was initiated.

During FY2002, renovations to the Oceanic Sequestration Laboratory in Building 84, Rooms 119 and 125 were completed and the HWTF and supporting facilities were constructed. The HWTF is now operational and observations of CO_2 drops under simulated deep-ocean conditions can be seen.

Benefits

This project will provide useful information and models for the development and storage optimization of CO_2 in our oceans. By injecting carbon dioxide into the ocean at depths greater than 1500m, the risk of unnecessary human contact is removed and the carbon dioxide is placed as far from the atmosphere as possible. Additionally, by capturing carbon dioxide and sequestering it, harmful emissions into the atmosphere are prevented that would further precipitate global warming.

CO_2 drop in the High-Pressure Water Tunnel at a simulated depth of 2000 m.

CONTACT POINTS

Robert Warzinski
Clean Air Technology Division
National Energy Technology Laboratory
P.O. Box 10940
626 Cochrans Mill Road
Pittsburgh, PA 15236
412-386-5863
robert.warzinski@netl.doe.gov

Curt White
Carbon Sequestration Focus Area Leader
National Energy Technology Laboratory
P.O. Box 10940
626 Cochrans Mill Road
Pittsburgh, PA 15236
412-386-5808
curt.white@netl.doe.gov

*Factsheets Under Development

Geology and reservoirs simulation for coal seam sequestration*
-NETL

Page left blank to accommodate 2-sided printing

*Factsheets Under Development

Geology and reservoirs simulation for brine field*
-NETL

Page left blank to accommodate 2-sided printing

PROGRAM facts

U.S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

Mineral Sequestration

07/2000

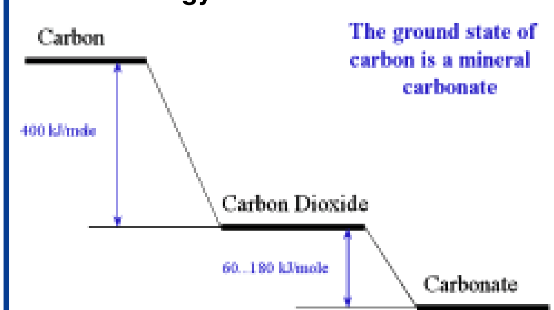
MINERAL CARBONATION STUDY PROGRAM

Description

The availability of clean, affordable energy is essential for the prosperity and security of the United States, as well as the rest of the world. About 85% of the energy used in the US is derived from fossil fuels, and continued dependence on these fuels is expected well into the 21st century. The continuing demand for energy and the associated rising CO_2 concentration in the atmosphere may have potentially large impacts on climate change. Comprehensive measures, including CO_2 sequestration, would be required to reduce CO_2 emissions while sustaining the demand for energy. Several methods have been suggested for sequestering CO_2, all of which have advantages and disadvantages. Among them, mineral carbonation is a relatively new and less-studied method with potential to sequester substantial amounts of CO_2.

Mineral carbonation, alternately referred to as Mineral Sequestration, is the reaction of CO_2 with non-carbonate minerals such as olivine and serpentine to form geologically stable mineral carbonates. Mineral carbonation could be realized in two ways. First, minerals could be mixed and reacted with CO_2 in a process plant. Second, CO_2 could be injected into selected underground mineral deposits for carbonation, similar to geological sequestration. Using mineral carbonation to reduce CO_2 emissions has many potential advantages such as:

Energy States of Carbon



Mineral Carbonization occurs naturally

Long Term Stability. Mineral carbonates, the product of this process, are known to be stable over geological time frames. This process ensures permanent fixation rather than temporary storage of CO_2, thereby guaranteeing no legacy issues for future generations. Mineral carbonation mimics the natural weathering of rock.

Vast Capacity. The raw materials for binding CO_2 exist in vast quantities across the globe. Readily accessible deposits exist in quantities that far exceed even the most optimistic estimates of coal reserves.

Potential to Become Economically Viable. The overall process is exothermic and, hence, has the potential to become economically viable. In addition, its potential to produce value-added by-products during the carbonation process, such as strategically important metals, may further reduce its costs.

PARTICIPANTS

Albany Research Center
Albany, Oregon

Arizona State University
Tempe, Arizona

Los Alamos National Lab
Los Alamos, New Mexico

National Energy Technology Laboratory
Pittsburgh, Pennsylvania

Science Applications International Corporation
Pittsburgh, Pennsylvania

CONTACT POINT

Philip Goldberg
Program Coordinator
National Energy Technology Laboratory
(412) 386-5806
philip.goldberg@netl.doe.gov

MINERAL SEQUESTRATION HOMEPAGE

http://www.fe.doe.gov/products/gcc/index.html

NETL

Mineral Carbonation Study Program

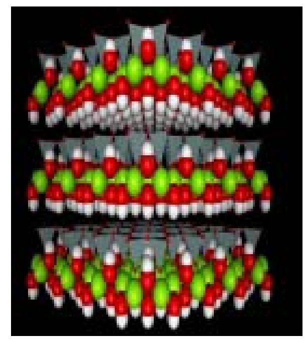
Despite these advantages, mineral carbonation processes will be practical only when two key issues are resolved. First, for sequestration purposes, a fast reaction route that optimizes energy management must be found. Second, issues with respect to the mining and processing activities required for mineral sequestration need to be quantified, especially concerns related to overall economics and environmental impact.

Goals

The primary goal of the mineral carbonation study is to generate a useful knowledge base that can lead to development of mineral CO_2 sequestration methods. To achieve this goal, the reaction mechanisms, heat requirements and environmental interactions must be understood well enough to permit engineering process development. A secondary goal is to acquire knowledge essential to understanding the reactions of CO_2 with underground minerals, in support of the U.S. Department of Energy's geological sequestration programs where CO_2 may be injected to deep saline aquifers or depleted oil or gas reservoirs. Knowledge of the reaction characteristics of CO_2 with various minerals at elevated pressures and temperatures such as those found deep underground will help scientists predict the long-term effects of such practices.

Elements

The team of researchers comprising this working group are pooling their knowledge and experimental capabilities in order to effectively conduct the structured program outlined below.



$Mg_3Si_2O_3(OH)$ - Atomic representation of serpentine structure (commonly called Lizardite)

***Study of Carbonation Reactions*.** Progress to date has been extremely encouraging. It has been found that finely ground serpentine $Mg_3Si_2O_5(OH)_4$, or olivine Mg_2SiO_4, will react with CO_2 in solutions of supercritical CO_2 and water to form magnesium carbonate $MgCO_3$. The reaction can be summarized as

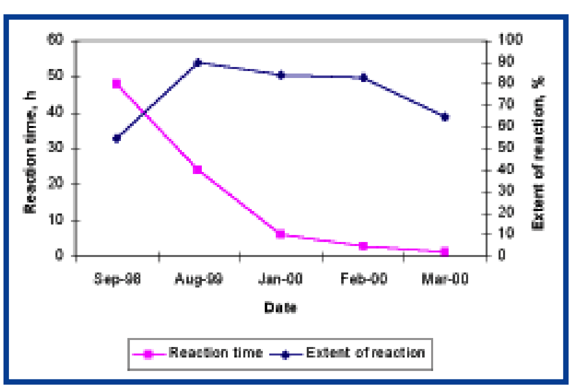
$$1/3\ Mg_3Si_2O_5(OH)_4 + CO_2 \text{ -----> } MgCO_3 + 2/3\ SiO_2 + 2/3\ H_2O$$

When the program first started, it required 24 hours to produce a 50% carbonation level using an olivine feedstock, reaction temperatures of 150-250°C and pressures of 85-100 bar. Through careful control of solution chemistry, the process has been accelerated so that 84% conversion of olivine can be achieved in just 6 hours. Furthermore, when heat pretreated serpentine is reacted using the same enhanced reaction process, approximately 80% conversion occurs in less than an hour. Carbonation studies are continuing utilizing highly instrumented reactors and atomic level simulations to optimize reaction conditions, and explore the use of catalysts and alternative feedstocks.

***System Feasibility*.** A life cycle assessment is under way to establish the feasibility of the baseline mineral sequestration concept with respect to system costs, development requirements and environmental attributes.

***Feedstock Characterization*.** Specific mineral deposits are being identified and characterized based upon potential co-location of mines and sequestration plants with fossil power plants. In addition, potential feedstock sources from industrial byproducts and waste streams are being examined.

These efforts are being conducted as part of Fossil Energy's Advanced Research and Technology Development efforts. The Mineral Carbonation Program is being managed through the National Energy Technology Laboratory's Environmental Product Division and is supported by the Coal Utilization Science, University Coal Research, and the Advanced Metallurgical Processes programs. The activities of the working group are being coordinated by the CUS program. Note that the group is seeking to interact with other interested researchers and industry stakeholders as a means to increase overall program scope and impact.



Mineral carbonation reaction time has been reduced from 48 hours to one hour over the period from Sept. 1998 to March 2000 at the Albany Research Center.

*Factsheets Under Development

Geologic sequestration core flow lab*
-NETL

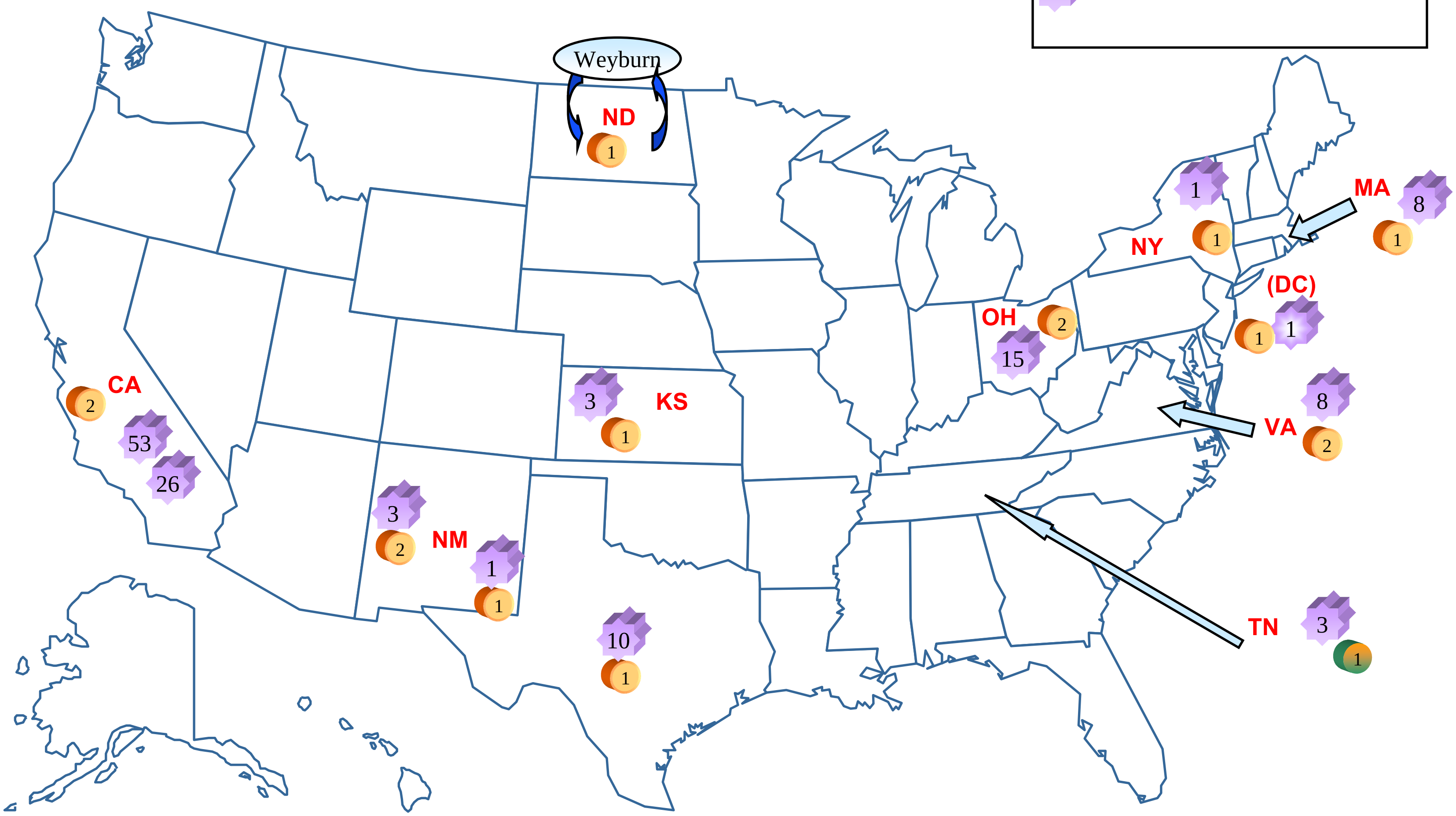
Page left blank to accommodate 2-sided printing

Measurement Mitigation & Verification

Page left blank to accommodate 2-sided printing

MMV Projects

LEGEND
- Number of MMV Projects
- MMV/Seq split projects
- Congressional District



*Doesn't include NETL

Project Title	Primary Contractor	Congressional District
Weyburn Carbon Dioxide Sequestration Project	Natural Resources Canada - CANMET	*Canada*
Natural Analogs for Geologic Sequestration	Advanced Resources International	VA08
A Sea Floor Gravity Survey of the Sleipner Field to Monitor CO_2 Migration	University of California, San Diego	CA53
Application and Development of Appropriate Tools and Technologies for Cost-effective Carbon Sequestration	The Nature Conservancy (TNC)	VA08
Development of a Carbon Management Geographic Information System for the US	MIT	MA08
Carbon Sequestration in Reclaimed Mined Soils of Ohio	Ohio State University Research	OH15
MIDCARB (Interactive Digital Carbon Atlas)	University of Kansas Center for Research	KS03
INS Soil Carbon Analyzer	BNL	NY01
Sequestration of CO_2 in a Depleted Oil Reservoir	Sandia National Laboratories	NM01
Ecosystem Dynamics and Econ. Anal	LANL	NM03
GEO SEQ Project (Project in Sequestration Area)	LBNL	CA09
GEO SEQ Project	LLNL	CA10
GEO SEQ Project	ORNL	TN03
Applied Terrestrial Carbon Sequestration	LANL	NM03
Development of Science-Based Permitting Guidance for Geologic Sequestration of CO_2 in Deep Saline Aquifers Based on Modeling and Risk Assessment	University of Texas at Austin	TX10
Stored CO_2 & Methane Leakage Risk Assessment and Monitoring Tool Development: CO_2 Capture Project Phase 2	BP Corporation North America Inc	DC01
Assessing Fossil Fuel and Recent Carbon Pools in Reclaimed Mined Soils	Ohio State University Research Foundation	OH15
Low Cost Open-Path Instrument for Monitoring Atmospheric Carbon Dioxide at Sequestration Sites	California Institute of Technology	CA26

(NETL projects not included)

Measurement Mitigation and Verification

Technology Target

•Indirect monitoring technology acceptable to permitting agency
•Direct CO_2 monitoring to detect leaks
•Resevoir monitoring test
•Demonstrate advanced videography for accurate remote estimates carbon inventories

- Understanding of equilbria between multi component gases, oil, and water
- Reliable monitoring and verification technology for CO_2 storage sites
- Computer simulation model to effectively monitor CO_2 depleted oil resevoirs, abandoned coal mines, and saline aquifiers
- Instrumentation and measurement protocols for carbon inventories in soils, forests, and geologic formations

Advanced Resources International
- Document empirically the capability of depleted oil and gas fields to sequester CO_2 safely and securely

SNL/LANL
- Computer simulation model for field test including measurement of fluid pressure changes for depleted oil resevoirs

Dakota Gasification/CANMET
- Wayburn project
- Develop monitoring techniques (surface Seismic & tracer injection)

LANL
- Applied sequestration partnership

BP
- Risk assessment and monitoring tools development

GEO-SEQ
LBNL – Seismic & EM Imaging
LLNL – Electrical Imaging
ORNL – Isotope tracers

Nature Conservancy
- Demonstrate and refine the tools and methodolgies for cost-effective, verified measurements of the long-term potential of various carbon sequestration and land use emissions avoidance strategies

University of California
- Sleipner sea floor survey

Ohio State
- Reclaimed mined soils of Ohio

Ohio State University Research Foundation
- Develop and test procedures to determine size of coal-derived carbon in reclaimed mined lands

BNL
- Non-invasive soil carbon scanning system

Univ. of Kansas
Construct database to evaluate geological locations and characteristics of CO_2 sources. Modeling and Assessment

MIT
Development of a carbon management GIS for US

University of Texas at Austin
- Permitting, modeling, and risk assessment

Cal Tech
- Develop instruments that will measure and monitor CO_2 emissions for geological sequestration sites

Measurement Mitigation & Verification Project Fact Sheet List

Project Title	Primary Contractor	Fact Sheet Listing
Weyburn Carbon Dioxide Sequestration Project	Natural Resources Canada - CANMET	M-5
Natural Analogs for Geologic Sequestration	Advanced Resources International	M-7
A Sea Floor Gravity Survey of the Sleipner Field to Monitor CO_2 Migration	University of California, San Diego	M-9
Application and Development of Appropriate Tools and Technologies for Cost-effective Carbon Sequestration	The Nature Conservancy (TNC)	M-11
Development of a Carbon Management Geographic Information System for the US	MIT	M-13
INS Soil Carbon Analyzer	BNL	M-15
National Carbon Sequestration Database and Geographical Information System (NATCARB)	University of Kansas Center for Research	M-17
Carbon Sequestration in Reclaimed Mined Soils of Ohio	Ohio State University Research	M-19
Sequestration of CO_2 in a Depleted Oil Reservoir	Sandia National Laboratories / LANL	M-23
GEO SEQ Project (Project in Sequestration Area)	LBNL, LLNL, ORNL	Factsheet in Sequestration
Development of Comprehensive Monitoring Techniques to Verify the Integrity of Geologically Sequestered Carbon Dioxide	NETL	M-25
Development of Simulation Tools for Sequestration and Retention of CO_2 in Permeable Media*	NETL	M-27
Applied Terrestrial Carbon Sequestration	LANL	M-29
Development of Science-Based Permitting Guidance for Geologic Sequestration of CO_2 in Deep Saline Aquifers Based on Modeling and Risk Assessment	University of Texas at Austin	M-31
Stored CO_2 & Methane Leakage Risk Assessment and Monitoring Tool Development: CO_2 Capture Project Phase 2*	BP Corporation North America Inc	M-33
Assessing Fossil Fuel and Recent Carbon Pools in Reclaimed Mined Soils	Ohio State University Research Foundation	M-35
Low Cost Open-Path Instrument for Monitoring Atmospheric Carbon Dioxide at Sequestration Sites	California Institute of Technology	M-37

(BP CCP and UCR projects not included)

* Factsheet Under Development

PROJECT facts

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

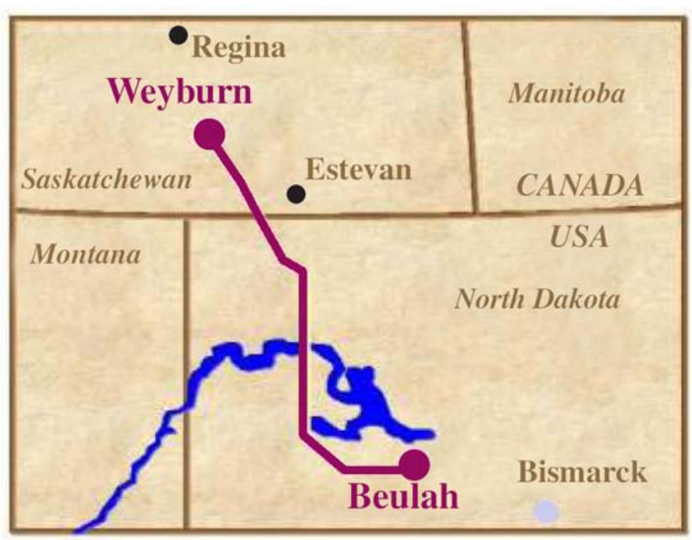
Sequestration

03/2005

WEYBURN CARBON DIOXIDE SEQUESTRATION PROJECT

Background

The Weyburn carbon dioxide (CO_2) sequestration project is intended to expand the knowledge base on formation capacity, transport, fate, and storage integrity of CO_2 injected into geologic formations. Use of new reservoir mapping and predictive tools (surface seismic and tracer injection) to develop a better understanding of the behavior of CO_2 in a geologic formation in conjunction with the Weyburn unit is being addressed by EnCana and Dakota Gasification Company. Weyburn Field, in southwestern Saskatchewan, Canada, was discovered in 1954. Starting in 2001, several tons per day of CO_2 have been pumped into this reservoir to produce incremental oil in a procedure known as enhanced oil recovery (EOR). The CO_2 is being transported by pipeline 330 km from the Great Plains Synfuels Plant in Beulah, North Dakota. It is expected that approximately 50% of the CO_2 will remain locked up with the oil that remains in the ground. The 50% that comes to the surface with the produced oil will come out of solution as the pressure drops and be recycled back to the injection wells. This work will examine the way CO_2 moves through the reservoir rocks, the precise quantity that can be stored in a reservoir, and how long the CO_2 could be expected to remain trapped in the underground formation.



Pipeline Route from North Dakota Gasification Plant to Weyburn Oil Field

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Karen Cohen
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-6667
karen.cohen@netl.doe.gov

Primary Project Goal

The goal of the Weyburn CO_2 Sequestration Project is to enhance the knowledge base and understanding of the underground sequestration of CO_2 associated with EOR. The Weyburn site provides a unique and cost effective opportunity to obtain data to model and predict the long-term storage of CO_2 in a geologic formation.

Objectives

- To show that sequestration into geologic formations can provide long-term storage of CO_2.
- To determine how much CO_2 is actually stored during EOR operations.
- To monitor and verify the amount of CO_2 that is sequestered.
- To study the dependence of CO_2 storage on geology.
- To find ways to increase CO_2 sequestration without compromising EOR operations.

Installation of CO_2 Pipeline

Accomplishments

- The project is on target to be completed by July, 2004.
- Approximately 71% of the CO_2 expected at the start of the project has been injected into the Weyburn site. Cumulative CO_2 injection as of June 30, 2003, was 69.6 billion standard cubic feet.
- Regional geological mapping is nearly complete.
- Regional hydrogeological mapping has identified 15 aquifers.
- The mineralogy of 100 reservoir core samples has been determined.
- An initial version of the CO_2 storage economic model, which includes the economics of CO_2 supply, transportation and storage, either stand alone or as an EOR operation has been completed.
- Risk assessment is continuing.

Benefits

This project will provide significant opportunities for the U.S. to enhance existing monitoring technologies for CO_2 sequestration in geologic formations. This expertise will benefit future large scale sequestration of CO_2 in the U.S. Global warming is an international issue, and the development of new technologies will help create new capabilities in the U.S., thus benefiting the U.S. In addition, this project will use U.S. generated CO_2 that would otherwise be discharged to the atmosphere. Knowledge obtained from this project will enable DOE to inform public policy makers, the energy industry, and the general public by providing reliable information and analysis of geological sequestration of CO_2 in association with EOR.

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

Provinces of Saskatchewan and Alberta

European Community (EC)

Petroleum Technology Research Council (PTRC)

Research Institute for Environmental Technology (RIET)

Lawrence Berkley National Laboratory

EnCana, Saskatchewan Power, Nexent, BP, Transalta

Dakota Gasification Company

University of Alberta

Colorado School of Mines

University of Regina

University of Saskatchewan

COST

Total Project Value
$26,588,000

DOE/Non-DOE Share
$4,000,000 / $22,588,000

Project 282.pmd

PROJECT facts

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

Sequestration

07/2004

Natural Analogs for Geologic Sequestration

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

David Hyman
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-6572
david.hyman@netl.doe.gov

Scott Stevens
Advanced Resources International
1110 North Glebe Road
Suite 600
Arlington, VA 22201
703-528-8420

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

Background

Large geologic deposits of high-purity carbon dioxide (CO_2), created entirely by natural geologic processes, occur in many sedimentary basins. They have acted as relatively stable repositories for CO_2 over many thousands of years and prove that geologic sequestration offers a secure, environmentally sound way of storing CO_2. Most importantly, they provide an excellent natural laboratory in which to study the effects of long-term CO_2 exposure on the reservoir minerals. These conditions cannot be replicated by short term laboratory experiments or geologic sequestration tests. CO_2 fields may be viewed as unique "natural analogs" that can be used to assess crucial aspects of geologic sequestration. These assessments would include: integrity of storage, candidate site screening and selection, and operational safety and efficiency. Thus, these CO_2 deposits offer considerable potential for understanding and publicizing geologic sequestration and can serve to build public confidence in this CO_2 management technique.

At present, five large natural CO_2 fields in the United States provide a total of 25 million tons of carbon dioxide that is injected into oil fields for enhanced oil recovery (EOR). This project will perform a multi-disciplinary geologic engineering study of U.S. CO_2 deposits. The overall objective is to compare the naturally occurring CO_2 reservoirs with the capability of depleted oil and gas fields to securely and economically sequester carbon dioxide.

Primary Project Goal

The overall goal is to study natural CO_2 fields to document empirically, both to the scientific community and the public at large, the capability of depleted oil and gas fields to sequester carbon dioxide safely and securely. The effort will also investigate long-term reactions between CO_2 and the various minerals in the reservoir and cap rocks.

Objectives

- Evaluate the safety and security of geologic sequestration
- Adapt specialized CO_2 operations technology to an emerging sequestration industry
- Document analogs for public review

Natural Analogs for Geologic Sequestration

PROJECT PARTNERS

Advanced Resources International
Kinder Morgan CO_2 Company, Ltd.
Ridgeway Petroleum Corporation
British Geological Survey NASCENT Project
Australian Petroleum Cooperative Research Center

COST

Total Project Value:	$1,736,390
DOE Share:	$1,123,390
Non-DOE Share:	$ 613,000

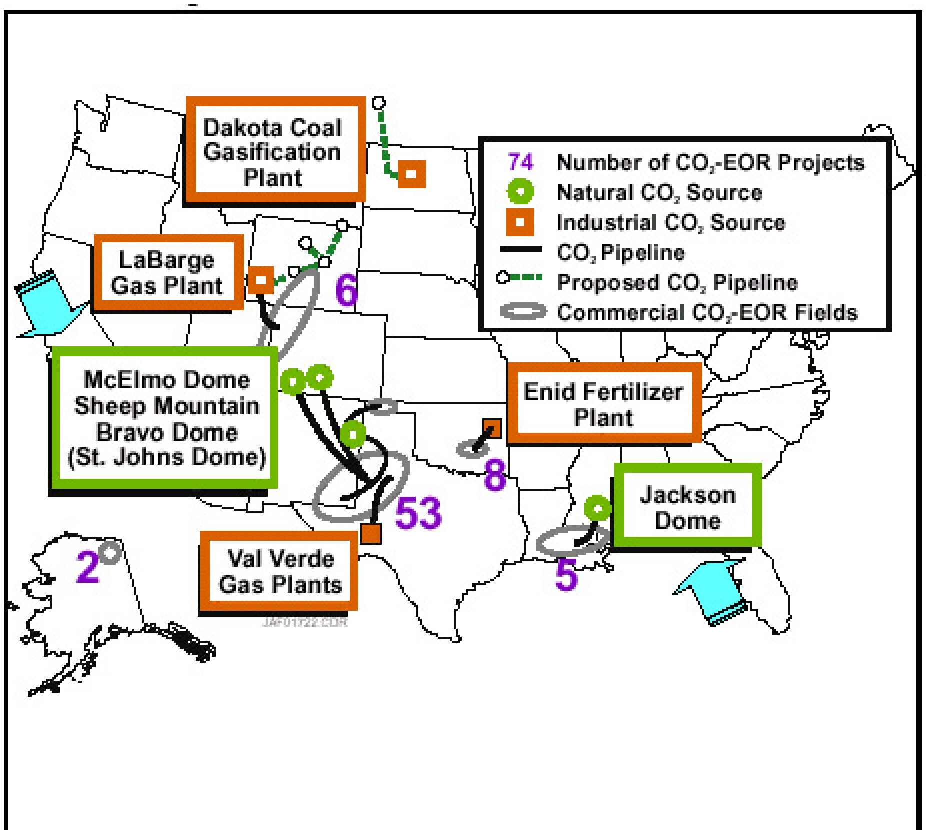
- Evaluation of environmental and safety related factors will be made based on the results of a geochemical analysis of CO_2 impacts and geochemical modeling

Accomplishments

Literature reviews and collection of geologic and reservoir data have been performed. ARI is about one-third of the way towards completing the first comprehensive analysis of three large natural CO_2 fields: Kinder Morgan's McElmo field in Colorado, Ridgeway's St. Johns Dome in Arizona and New Mexico, and Denbury Resources' Jackson Dome field in Mississippi. Existing well log and other geologic information has been collected and is currently being used to build robust geologic models of the three fields.

Benefits

This project will provide information that can be used to develop technologies for safe and secure sequestration of CO_2 in natural geologic formations. Furthermore, the project provides an opportunity to study CO_2 sequestration in a non-intrusive manner at natural sites and to obtain data not otherwise obtainable on the long-term effect of CO_2 on mineral strata.



Location of natural CO_2 study sites in the USA and the CO_2 infrastructure for EOR projects

Proj216.pmd

PROJECT facts

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

Sequestration

01/2004

A SEA FLOOR GRAVITY SURVEY OF THE SLEIPNER FIELD TO MONITOR CO_2 MIGRATION

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

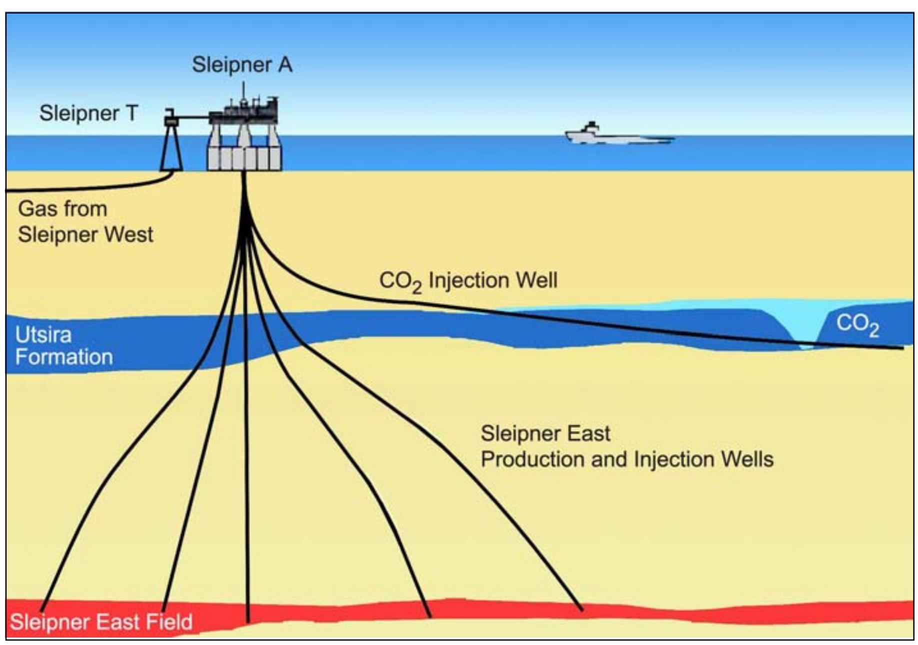
David Hyman
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-6572
david.hyman@netl.doe.gov

Mark Zumberge
University of California, San Diego
9500 Gilman Drive
La Jolla, CA 92093
858-534-3533
mzumberge@ucsd.edu

Background

In order for geologic sequestration of carbon dioxide to be a viable option for reducing greenhouse gas emissions, techniques have to be developed to monitor the emplacement and sequestration of carbon dioxide in an underground geologic environment. This project seeks to apply high precision gravitational surveying techniques to quantify the change in the local gravitational field associated with the sequestration of carbon dioxide.

The Sleipner West natural gas field in the North Sea produces carbon dioxide. To avoid paying a tax on carbon dioxide emitted into the atmosphere, Statoil, which owns the field, has been injecting most of this carbon into a saline aquifer, the Utsira formation, about 1,000 meters beneath the sea. The Utsira formation is a permeable sandstone saline aquifer about 200-250 meters thick and is overlain by mudstone. The studied site covers an approximately 3 x 7 km area, and the water depth averages about 300 meters.



Schematic Cross-section of geologic strata for the Sleipner project

CUSTOMER SERVICE

800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

University of California, San Diego

Statoil

COST

Total Project Value:
$384,860

DOE/Non-DOE Share:
$224,860 / $160,000

Primary Project Goal

The primary project goal is to quantify the change in the local gravitational field associated with the sequestration of carbon dioxide in the saline aquifier below the bed of the North Sea so as to assess the ability of microgravity techniques to monitor geologically sequestered carbon dioxide. This study will utilize high precision gravitational surveying techniques along with seismic data.

Objectives

- Perform a high precision gravitational survey over the portion of the Utsira formation undergoing carbon dioxide sequestration
- Reduce and analyze the gravitational potential field data to discriminate zones of geologic formation infused with carbon dioxide
- Use results of this application of high precision gravitational surveying techniques to monitor sequestration of carbon dioxide in a saline aquifer

Accomplishments

Successfully conducted a microgravity survey with better-than-expected repeatability

Benefits

This project will develop new techniques to monitor CO_2 migration in a saline aquifer. Successful monitoring and verification are necessary to confirm that saline aquifers are a satisfactory repository for CO_2 and can be used to reduce greenhouse gas intensity by providing a viable geologic CO_2 sequestration option.

Deployment of the Remotely Operated Vehicle with a Deep Ocean Gravimeter (ROVDOG)

Proj247.pmd

PROJECT facts

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

Sequestration

04/2003

APPLICATION AND DEVELOPMENT OF APPROPRIATE TOOLS AND TECHNOLOGIES FOR COST-EFFECTIVE CARBON SEQUESTRATION

CONTACT POINTS

Scott M. Klara
Sequestration Product Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

John Litynski
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-1339
john.litynski@netl.doe.gov

Bill Stanley
The Nature Conservancy
4245 North Fairfax Drive
Arlington, VA 22201
703-841-5823
bstanley@tnc.org

TOTAL ESTIMATED COST

Total Project Value	$2,065,425
DOE	$1,652,340
Non-DOE Share	$ 413,085

Background

According to the Intergovernmental Panel on Climate Change (IPCC), deforestation accounts for about 20 percent of annual global emissions of carbon dioxide (CO_2), the primary greenhouse gas (GHG). The IPCC estimates that 12 to 15% of the fossil fuel CO_2 emissions between 1995 and 2050 could be offset through slowing tropical deforestation, allowing these forests to regenerate, and engaging in plantation plantings and other forms of agroforestry.

There is great potential for such cost-effective carbon sequestration projects both in the United States and abroad. However, without the development and refinement of tools and technologies that allow accurate and cost-effective assessment of the amount of carbon sequestered, these approaches may not be recognized as a credible means for reducing GHG. Through the ongoing development and implementation of carbon sequestration projects on a demonstration scale, The Nature Conservancy is participating in a cooperative agreement with the Department of Energy to explore the compatibility of carbon sequestration in terrestrial ecosystems with the conservation of biodiversity. The Conservancy's first involvement in assessing this approach came in 1994 with the development of the Rio Bravo Carbon Sequestration Pilot Project in Belize, in cooperation with several partners. Since then, several other projects have been initiated with a variety of partners.

This project will focus on gaining cost-effective, verified measurements of the long-term potential of various terrestrial carbon sequestration strategies and assessing land use practices that avoid emissions of CO_2. The project will use newly developed aerial and satellite-based technology to study forestry projects in Brazil and Belize to determine their carbon sequestration potential and will also test new software models to predict how soil and vegetation store carbon at sites in the United States and abroad.

Primary Project Goal

The primary goal of this project is to refine the tools and methodologies for cost-effective, verified measurements of the long-term potential of various carbon sequestration strategies and assessing land use practices that avoid emissions of CO_2, using actual projects as proving grounds.

Application and Development of Appropriate Tools and Technologies for Cost-Effective Carbon Sequestration

PARTNERS

The Nature Conservancy (TNC)

Winrock International Institute for Agricultural Development

The Society for Wildlife Research (SPVS)

Programme for Belize

Comite de Defensa de la Fauna y Flora (CODEFF)

Universidad Austral de Chile

Los Alamos National Laboratory

Colorado State University

Stephen F. Austin State University

Virginia Technical University

ADDITIONAL SUPPORT

American Electric Power
General Motors
Texaco

CUSTOMER SERVICE

800-553-7681

WEBSITE

www.netl.doe.gov

Objectives

- Improve carbon monitoring and lower its cost
- Develop land use trend models to project potential CO_2 offsets
- Evaluate and standardize carbon monitoring methods and procedures
- Assess domestic land-use options for reducing greenhouse gases
- Develop software for initial feasibility screening of potential domestic projects.

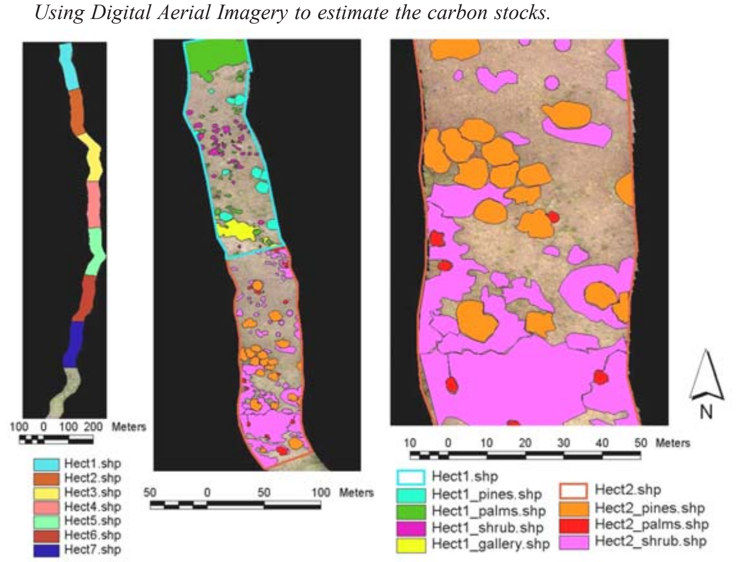
Accomplishments

Advanced videography has been applied for pine savannah analysis in Belize. Feasibility studies on several different U.S. ecosystems have been initiated to determine for which of these ecosystem types carbon sequestration is a viable option. The GEOMOD spatial analysis tool has been used to determine and validate baseline analyses. An alternative baseline method developed by TNC, called the Euclidean Distance between Agriculture and Forest (EDAF) method, has been further refined in baseline analyses in Brazil. A technical advisory panel was organized to address the issues associated with baseline and leakage estimates. In addition, soil monitoring is being conducted using laser-induced breakdown spectroscopy (LIBS), being developed by the Los Alamos National Laboratory.

Benefits

This project is very important because it is validating technology and developing protocols to measure carbon both in soils and in above ground vegetation. Although most of the sites being surveyed are in South America, the technology is easily transferable to other areas.

Examples of interpretation of sub-vegetation types within 1 ha "plots" in the Pine-Savanna Vegetation in the Rio Bravo Carbon Sequestration Pilot Project Using Digital Aerial Imagery to estimate the carbon stocks.



Designing a destructive sampling protocol for a heterogeneous landscape. Guaraqueçaba Climate Action Project, Paraná, Brazil.

Proj231.pmd

PROJECT facts

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

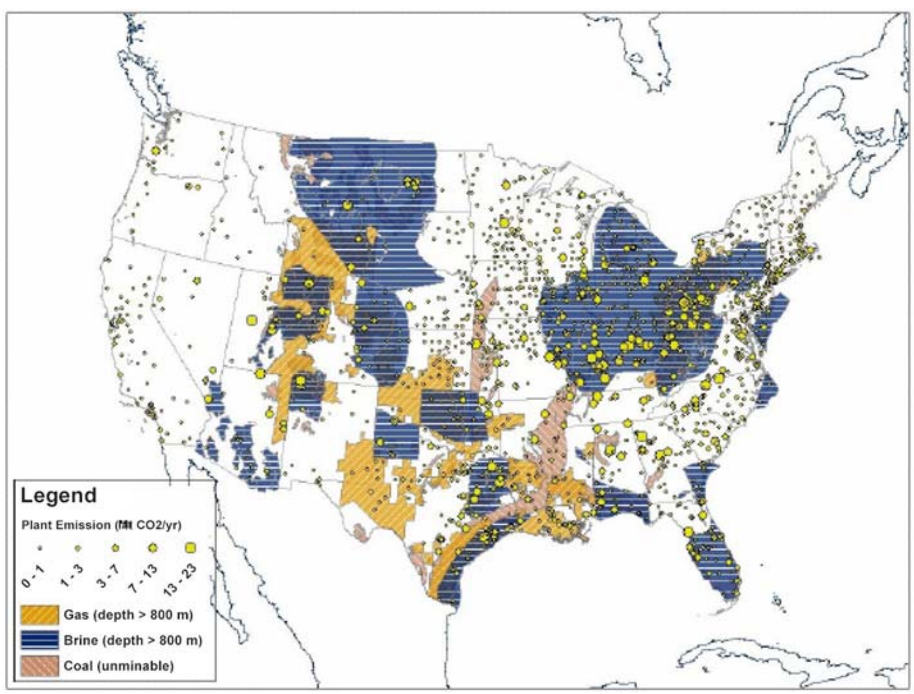
Sequestration

04/2004

DEVELOPMENT OF A CARBON MANAGEMENT GEOGRAPHIC INFORMATION SYSTEM (GIS) FOR THE UNITED STATES

Background

This project will develop tools to provide DOE managers with the capability for real-time display and analysis of CO_2 sources, potential sequestration sinks, and other data, such as transportation corridors, within a spatial database. This type of program can assist decision makers by providing visual access to high quality, current, consistent data obtained from distributed datasets. The main tool being used is a Geographic Information System (GIS). The GIS tool will be used to model, analyze, and display spatial relationships between the data. The Massachusetts Institute of Technology's (MIT) Carbon Management (CM) system will employ GIS tools to support decision making within the CM system. MIT will use GIS software to prepare a user friendly model, which DOE will receive at the end of the project. Various social, economic, and political aspects of sequestration will also be part of the project.



A selection of data under consideration in MIT's Carbon Management System.

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Dawn Chapman
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-4133
Dawn.Chapman@netl.doe.gov

Howard Herzog
Massachusetts Institute of Technology
1 Amherst Street, Building E40-471
Cambridge, MA 02139
617-253-0688
hjherzog@mit.edu

MIT will take a top-down approach to analyzing the potential for CO_2 capture and storage in the U.S. In order to avoid duplication of effort while conducting this effort, MIT will work closely with the ongoing Midcontinent Interactive Digital Carbon Atlas and Relational Database (MIDCARB) Consortium project, which is presently concerned with determining the carbon sequestration potential of five Midwestern states. The primary use of the Carbon Management GIS will be as a systems analysis tool that can be used on a local, regional, or national scale.

Primary Project Goal

The overall objective of this project is to develop an analysis tool to aid in the development and deployment of carbon capture and sequestration technologies within the U.S.

Objectives

- To develop a Carbon Management GIS for the purpose of capturing, integrating, manipulating and interpreting data relevant to carbon capture and sequestration.
- To use commercially available software and databases in the development of the CM system.
- To use freely available "core" data and convert it to an appropriate form for the GIS.
- To further develop supplemental data on costs and social issues, based on past work.
- To develop computer codes to perform analyses specific to carbon sequestration systems.
- To work with MIDCARB to provide internet access to the developed software in a manner similar to that already done by MIDCARB.
- To use the finished product to perform initial analyses.

Accomplishments

MIT has identified and incorporated data into the GIS. While this will be a continuing process, an initial set of data has been gathered into the GIS so basic analyses could be initiated. Installation of the web server and GIS viewer has been completed. MIT has produced a working prototype that incorporates the following points:

- Data requirements for primary carbon dioxide system: sources, transportation infrastructure and sinks.
- Data requirements for factors that may modify costs in the system: geography, topography.

Storage cost estimation has also been initiated. MIT has produced a cost map for single brine formation in Texas manually using ArcGIS Spatial Analysis Tools.

Benefits

One of the options for mitigating CO_2 emissions from power plants and other point sources is sequestration in geologic formations. However, to minimize costs, sources and sinks should be in close proximity. The software being developed in this project will permit rapid visualization of the relationship between CO_2 sources and potential sequestration sites. It will ultimately aid the DOE in the development of meaningful and economically feasible sequestration demonstration projects. Such projects are essential if sequestration is to become technically, economically, environmentally, and socially acceptable.

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

Massachusetts Institute of Technology

Midcarb consortium

COST

Total Project Value
$1,062,106

DOE/Non-DOE Share
$849,685/$212,421

Proj285.pmd

PROJECT

facts

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

Sequestration

02/2004

IN FIELD, CONTINUOUS, NON-INVASIVE SOIL CARBON SCANNING SYSTEM

Background

Global warming is promoted by anthropogenic CO_2 emissions into the atmosphere, while at the same time it is partially mitigated by carbon sequestration in the terrestrial ecosystem. However, a better understanding and monitoring of the underground carbon processes is cardinal for evaluating various strategies for carbon sequestration and quantification of the carbon stores for credits.

Brookhaven National Laboratory developed an instrument for carbon analysis in soil based on inelastic neutron scattering (INS). INS offers a non-invasive means for continuously monitoring the soil carbon inventory over both specific plots and large areas. This technique can significantly improve quantification of the efficacy of carbon sequestration methodologies. The proposed instrument enables a continuous scan and evaluates the mean soil carbon content in the field to a depth of about 20cm. This project offers to fill a void that exist in instrumentation in the area of monitoring belowground carbon processes in a fashion that is repetitive and provides a representative value for the soil carbon content over large areas. At present, carbon concentrations in soil are assessed indirectly using analytical models, and directly by taking core samples and subsequently subjecting the samples to physical and chemical analysis in the laboratory. However, the extensive variability of soil carbon both laterally and with depth in nearly every type of terrain requires large number of samples for statistically meaningful determination of mean carbon concentration with an acceptable level of error. This analysis process is labor intensive, expensive, slow and not amenable to up scaling for analysis of soil carbon at continent to global scales. Two new approaches utilizing laser induced breakdown and near-infra-red spectroscopy, are being developed. These two new techniques although less labor intensive are invasive and represent a micro-point and surface measurements. Thus they are irreproducible for the specific site sampled, since the point of measurement, in each of the cases, is essentially destroyed. The new instrument being developed at BNL overcomes the shortcomings of the current technologies.

Components of a future system to be assembled for field measurements.

Primary Project Goal

The purpose of this project is the development of an instrument with the capability for safe, rapid, non-destructive, multielemental, in situ soil carbon quantification and profiling over large areas and volumes.

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

John Litynski
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-1339
john.litynski@netl.doe.gov

Lucian Wielopolski
Brookhaven National Laboratory
Upton, NY 11973
631-344-3656
lwielo@bnl.gov

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

Brookhaven National Laboratory

COST

Total Project Value:
$459,202

DOE/Non-DOE Share:
$459,202 / $0

Objectives

- The short-term objectives of present work are to construct a deployable prototype INS scanner for non-destructive soil carbon measurements in the field and to perform calibration and field verification of the system.
- The long-term objective is to perform measurements in various soil types in which the soil carbon content is well characterized. The system also will be used for comparison and possible development of conversion factors to scale specific point measurements obtained by other means to large field values.

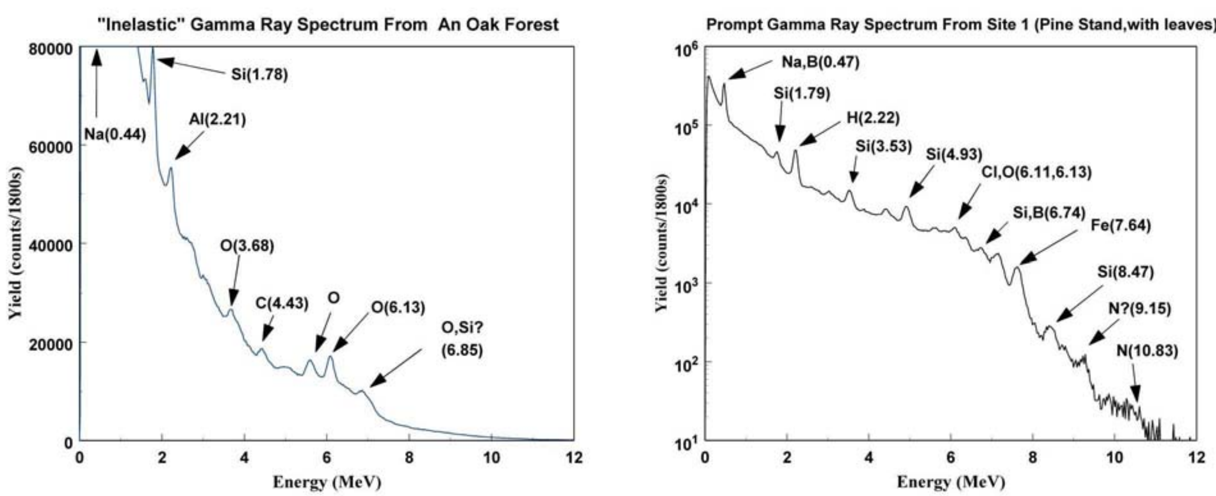
Accomplishments

- A patent application for an INS system to measure carbon in soils is pending.
- During FY 2003 the first set of outdoor calibration measurements in a 4'x 5'x1.5' sand pit was obtained using sand mixed with known amounts of carbon.

Field measurement in an oak forest using an INS prototype instrument.

Benefits

This project is developing a robust, flexible, non-invasive, scanning system for in situ monitoring and verifying temporal changes in soil carbon over large areas. The anticipated benefit from such a system is the ability to monitor below ground carbon balances without disturbing the soil. Furthermore, the system enables continuous scanning of large areas thus providing a true mean carbon concentration in the soil. The proposed system enables, for the first time, repetitive measurement of the same site, thus allowing sequential monitoring of large areas. Collaboration with soil scientists from USDA ARC, as recommended by the NETL staff, will be established for final system testing using their well characterized fields.



Inelastic and prompt gamma spectra showing the results of the INS system.

Proj266.pmd

PROJECT facts

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

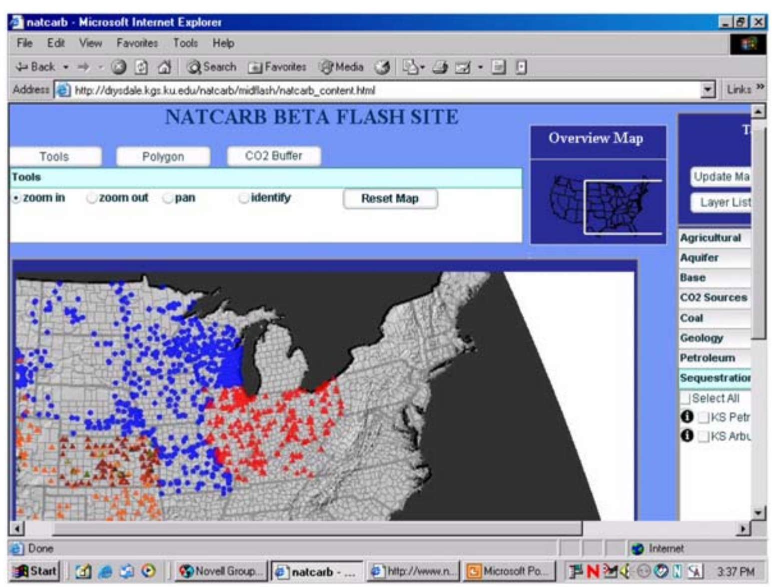
Sequestration

08/2004

National Carbon Sequestration Database and Geographical Information System (NATCARB)

Current federal energy policy assumes that fossil fuels will continue to be the primary source of energy for the United States and the world well into the 21st century. However, there is growing concern about the possible effect that the increasing atmospheric concentration of carbon dioxide (CO_2) is having on climate change. For this reason, it may become necessary to manage anthropogenic CO_2 emissions. Sequestering CO_2 in geological reservoirs may be one way to safely store carbon over long periods of time, provided the necessary data and tools to analyze the geological feasibility and costs can be developed. A similar possibility exits for terrestrial sequestration where carbon is stored in soils and vegetation.

The National Carbon Sequestration Database and Geographical Information System (NATCARB) started as a joint project among the State Geological Surveys of five Midwestern states (Illinois, Indiana, Kansas, Kentucky, and Ohio), with funding from the Department of Energy's National Energy Technology Laboratory. Later the project was expanded to include the seven regional partnerships established by the Department of Energy and a prototype to integrate databases for terrestrial sequestration with databases on geologic sequestration. The purpose of NATCARB is to assess the carbon sequestration potential in the United States and to develop a national Carbon Sequestration Geographic Information and Relational Database Management System covering the entire U.S. When completed, the digital spatial database will allow users to estimate the amount of CO_2 emitted by sources (such as power plants, refineries and other fossil fuel consuming industries) in relation to geologic reservoirs that can provide safe, secure sequestration sites over long periods.



Source: *http://drysdale.kgs.ku.edu/natcarb/midflash/natcarb.html*

Screen shot of the NATCARB interactive site

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Dawn Chapman
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-4133
dawn.chapman@netl.doe.gov

Tim Carr
University of Kansas Center for Research
2385 Irving Road
Lawrence, KS 66044
785-864-3441
tcarr@kgs.ku.edu

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

University of Kansas Center for Research

The US Geological Survey

The geological surveys in Illinois, Indiana, Kansas, Kentucky, and Ohio

The CO2 Regional Partnerships

COST

Total Project Value
$4,376,789

DOE/Non-DOE Share
$3,285,933/$1,090,856

Benefits

The NATCARB project will benefit the power industry by providing improved online tools for the real-time display and analysis of CO_2 sequestration data. The system links data on sources, sinks, and transportation facilities within a spatial database that can be queried online. NATCARB can assist decision makers by providing access to common sets of high quality data in a consistent manner. This database will prove invaluable should the nation reach the point were sequestration of CO_2 is necessary to prevent the buildup of greenhouse gases in the atmosphere.

NATCARB is organizing and enhancing the critical information about CO_2 sources and developing the technology needed to access, query, model, analyze, display, and distribute natural resource data related to carbon management.

Large stationary CO_2 emission sources are identified, located, and characterized. Potential CO_2 sequestration sites, including producing and depleted oil and gas fields, unconventional oil and gas reservoirs, uneconomic coal seams, abandoned subsurface mines, and saline aquifers, will be characterized to determine quality, size, and geologic integrity. All information will be available online through user query and will be provided through a single interface that will access multiple servers in various locations. This is one of the first demonstrations of a large-scale distributed database of natural resources and geological information. Access to the up-to-date technical information can be used at a regional or national level as a tool to minimize negative economic impacts and maximize the value of CO_2 sequestration for hydrocarbon recovery from oil and gas fields, coal beds, and organic-rich shales.

Primary Project Goal

The primary goal of this project is to construct a relational database management system with spatial query capabilities to evaluate the geographic distribution, physical characteristics, economic parameters, and potential geologic sequestration sites of CO_2 sources throughout the United States. A demonstration to link terrestrial/agricultural and geologic sequestration databases through Kansas State University is also planned.

Objectives

The objectives of this project are to:

- Expand the database originally designed to asses the geological CO_2 storage potential of five Midwestern states (Indiana, Illinois, Kansas, Kentucky, and Ohio) to include the entire U.S.
- Link terrestrial/agricultural and geologic sequestration databases through Kansas State University.
- Develop a national Carbon Sequestration Geographic Information and Relational Database Management System covering the U.S. and operating through a portal under the aegis of the National Energy Technology Laboratory website.
- Develop improved online tools to provide real-time display and analysis of CO_2 sequestration data.
- Enhance the current webpage by making it more user friendly with more advanced query capabilities and more options

Accomplishments

The NATCARB map server is active and currently running on the internet. The NATCARB interactive site can be utilized by accessing the following web address: *http://drysdale.kgs.ku.edu/natcarb/midflash/natcarb.html*. Reliable communication among the various servers has been established, and tools have been developed to query, display, and analyze CO_2 source, sink, and transportation data. Tools allow clients to query and plot emissions or production through time for a single source or a combination of sources across a region. Tools are also available to determine the solubility or physical properties of CO_2 under various conditions.

Not only is the NATCARB server connected to all the regional partnerships, but data on states not included in any of the partnerships has been entered into the database. To provide national coverage, data in real time is being pulled from the USGS-EROS center and from the Geography Network. Major CO_2 sources have been obtained from EPA databases, and data on major coal basins and coalbed methane wells was obtained from the EIA. Although this data is available through the NATCARB site, the databases are stored and managed by the partnerships.

Proj305.pmd

PROJECT facts

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

Sequestration

02/2004

CARBON SEQUESTRATION IN RECLAIMED MINE SOILS OF OHIO

Background

This research proposal is aimed at assessing the soil organic carbon (SOC) sequestration potential of reclaimed mined soils (RMS). Sites mined between 0 and 50 years ago will be identified in regions with similar ecological characteristics. The sites will be carefully selected with similar topography, climate, vegetation, and soil type. These sites will receive six different treatments. At least 50 soil samples will be collected from each treatment and will be analyzed to determine SOC, physical, chemical, and hydrologic properties. The spatial and temporal variations of SOC and the rate of sequestration in forest and pasture will be determined. The mechanisms of SOC sequestration and the potential of biosolids for reclamation will be assessed.

The data gathered will be used to test the following hypotheses: the potential of SOC sequestration in RMS depends on biomass productivity, root development in subsoil, and changes in mine soil properties resulting from the weathering of overburden material; the increase in SOC overtime is related to improvements in soil quality; the capacity of RMS to sequester SOC is a function of the type and duration of land use; the rate of SOC sequestration is related to changes in soil structure; carbon aggregation is influenced by the interaction between SOC and the silt/clay concentration and the mineralogical composition; the rate of SOC sequestration increases linearly with the rate of biosolids application and is proportional to the total amount and rate of release of mineralizable nitrogen; the rate of aggregation dependents upon the mineralizable carbon and nitrogen in the biosolids; and the SOC sequestration potential is related to its mechanical (porosity, strength) and hydrologic (hydraulic conductivity, infiltration rate, available water capacity) properties.

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

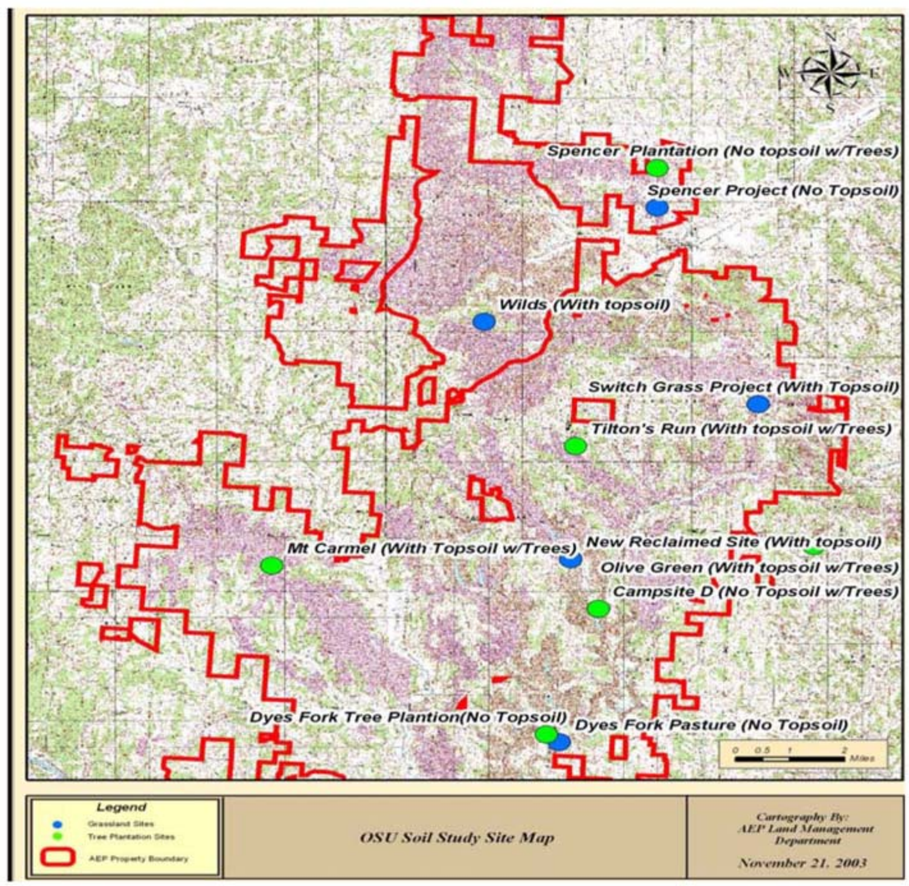
John Litynski
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-1339
john.litynski@netl.doe.gov

Rattan Lal
Ohio State University
School of Natural Resources
2021 Coffey Road
Columbus, OH 43210
614-292-9069
Lal.1@osu.edu

M.K. Shukla
Ohio State University
School of Natural Resources
2021 Coffey Road
Columbus, OH 43210

Primary Project Goal

The primary project goal is to assess the degree to which soil carbon sequestration in RMS can offset fossil fuel emissions, provide additional income to land owners through trading carbon credits, and strengthen the terrestrial carbon sequestration data base to assist policy makers on land use modifications to mitigate climate change due to greenhouse gas buildup in the atmosphere.



This map shows the locations of experimental sites

Objectives

- To assess the sink capacity of RMS of various ages to sequester SOC.
- To determine the rate of SOC sequestration and the spatial (vertical and horizontal) and temporal variations of SOC.
- To develop and validate a model for SOC sequestration rate.
- To identify the mechanisms of SOC sequestration in RMS.
- To assess the potential of different methods of soil reclamation to alter SOC sequestration rate, soil development, and soil mechanical and water transmission properties.
- To determine the relation between SOC sequestration rate and soil quality in relation to soil structure and hydrologic properties.

Accomplishments

Test sites, characterized by distinct age chronosequences of reclaimed minesoil, have been selected. The criteria for selection was: (i) reclaimed prior to the 1972 Ohio Mineland Reclamation Act or the 1977 surface mining reclamation and control act (SMRCA) and under continuous grass and forest and without topsoil application, and (ii) reclaimed after the 1972 Ohio Mineland Reclamation Act or, which made application of topsoil mandatory for reclamation, under continuous grass and forest and with topsoil application. Soil samples were collected from 0 to 15 cm and 15 to 30 cm depths and analyzed to determine soil organic carbon (SOC) concentration, total soil nitrogen concentration, pH and electrical conductivity for each sampling location.

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

Ohio State University

COST

Total Project Value:
$706,105

DOE/Non-DOE Share:
$563,491 / $142,614

Benefits

Soils represent a huge potential sink for carbon, and carbon trading could provide the incentive for landowners to modify land management practices to increase carbon sequestration in soils. However, for this to be possible, techniques have to be developed to quantify carbon take-up by soils, and the best treatments to promote carbon accumulation by soils and their associated vegetation need to be determined. This project is addressing both these issues, and its successful completion should yield significant benefits.

Over burden material after topsoil removal

An active mine site reclaimed in year 2003

Proj268.pmd

PROJECT **facts**

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

Sequestration

04/2003

Geologic Sequestration of CO_2 in a Depleted Oil Reservoir: A Comprehensive Modeling and Site Monitoring Project

CONTACT POINTS

Scott M. Klara
Sequestration Product Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Charles W. Byrer
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-4547
charles.byrer@netl.doe.gov

Norman R. Warpinski
Project Manager
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185
505-844-3640
nrwarpi@sandia.gov

Rajesh Pawar
Project Manager
Los Alamos National Laboratory
Los Alamos, NM 87545
505-667-6929
rajesh@lanl.gov

Background

Carbon dioxide (CO_2) injection into geologic formations is a promising strategy for the long-term sequestration of anthropogenic CO_2. This technique is likely to be needed to sustain the U.S.'s fossil fuel-based economy and to maintain our high standard of living. Subsurface injection of CO_2 into depleted oil reservoirs has the potential to be both cost effective and environmentally safe. However, CO_2 sequestration in oil reservoirs is a complex process spanning a wide range of scientific, technological, economic, safety, and regulatory issues. Detailed understanding of the many interactions is necessary before this option can become a safe and economic sequestration option, and its development requires a focused R&D effort by government and private industry.

Significant R&D gaps related to the sequestration of CO_2 in depleted oil reservoirs include the need to understand coupled physicochemical processes involving CO_2, water, oil, and reservoir rock; better estimates of the capacity of reservoirs for long-term sequestration; the ultimate fate of injected CO_2 (compared to short-term enhanced oil recovery); and improved remote (geophysical) monitoring technologies for accurately determining the dispersion of injected CO_2. Sandia National Laboratory and Los Alamos National Laboratory, along with New Mexico Tech, Colorado School of Mines and Kinder Morgan, have partnered with an independent producer, Strata Production Company, to investigate downhole injection of CO_2 into a depleted oil reservoir, the West Pearl Queen Field in New Mexico. This project is using a comprehensive suite of computer simulations, laboratory tests, and field measurements to understand, predict, and monitor the geochemical and hydrogeologic processes involved.

The following components are involved: geologic flow/reaction modeling; injection of CO_2 into a depleted oil-producing reservoir; geophysical monitoring of the advancing CO_2 plume; and laboratory experiments to measure reservoir changes due to CO_2 flooding. The models and data are being used to predict storage capacity and physical and chemical changes in reservoir properties, such as fluid composition, porosity, permeability, and phase relations. Science and technology gaps related to sequestration of CO_2 in depleted oil reservoirs will be identified as a result of this study.

Primary Project Goal

The overall objective of this project is to better understand, predict, and monitor CO_2 sequestration in a depleted sandstone oil reservoir. Injection into this reservoir was through an inactive well, while a producing well and two shutoff wells are being used for monitoring.

Geologic Sequestration of CO_2 in a Depleted Oil Reservoir: A Comprehensive Modeling and Site Monitoring Project

PARTNERS

Sandia National Laboratories

Los Alamos National Laboratory

New Mexico Tech University

Strata Production Company

Kinder-Morgan CO_2 Company

Colorado School of Mines

TOTAL ESTIMATED COST

Total Project Value	$4,830,000
DOE	$3,930,000
Non-DOE Share	$ 900,000

CUSTOMER SERVICE

800-553-7681

WEBSITE

www.netl.doe.gov

Objectives

- Characterize the oil reservoir and its capacity to sequester CO_2 .
- Predict multiphase fluid migration and interactions.
- Deploy and evaluate improved remote geophysical monitoring techniques.
- Measure CO_2/reservoir reactions.
- Conduct computer simulations and lab measurements of fluid flow .
- Assess and predict complex geologic sequestration processes.
- Inject several thousand tons of CO_2 into a depleted oil reservoir .
- Establish pre-injection baseline and assess post-injection reservoir conditions to validate model predictions.

Accomplishments

Current geologic and preliminary flow simulation results indicated the feasibility of CO_2 injection into a depleted oil reservoir. Simulations have predicted plume travel times and suggest that the combined saturation and pressure difference waves generated by injected CO_2 can be monitored through use of seismic surveys. Simulations also provide guidelines for geophysical monitoring (e.g., spacing of sources and receivers). Geochemical experiments with Queen Sandstones have been initiated to understand the potential for in situ mineralization. These experiments show that carbonate cements dissolve over time.

Approximately 2,100 tonnes of CO_2, equivalent to one day's emissions from an average coal-fired power plant, have been injected into the formation. An extensive three-dimensional geophysical survey was conducted prior to CO_2 injection to provide the best possible subsurface image of the reservoir. As the CO_2 entered the reservoir at a rate of about 40 tons/day and a pressure of 1,400 psi, scientists used highly sensitive equipment to acquire microseismic signals to help track the movement of the plume. After the CO_2 has been allowed to "soak" into the reservoir rock, a second 3-D seismic survey will be taken. These observations will begin to tell scientists the fate of the CO_2 plume and will be used to calibrate, modify, and validate modeling and simulation tools.

Benefits

This project takes advantage of unique test opportunities for a pilot scale field experiment in a pressure-depleted oil reservoir to predict and monitor the migration and ultimate fate of injected CO_2. The models and data developed will be used to predict storage capacity and physical and chemical changes in reservoir properties, such as fluid composition, porosity, permeability, and phase relations. Science and technology gaps related to engineering aspects of CO_2 sequestration will be identified in this study. In addition, a better understanding of CO_2/reservoir interactions will improve enhanced oil recovery (EOR) flooding practices.

Proj229.pmd

PROJECT facts
U.S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

08/2002

DEVELOPMENT OF COMPREHENSIVE MONITORING TECHNIQUES TO VERIFY THE INTEGRITY OF GEOLOGICALLY SEQUESTERED CARBON DIOXIDE

PRIMARY PARTNERS

National Energy Technology Laboratory
Brookhaven National Laboratory
Los Alamos National Laboratory
Sandia National Laboratory
West Virginia University
OPHIR Corp.
Strata Production Company
Pecos Petroleum

DOE FUNDING PROFILE

Prior FY's	$319,000
FY2002	$400,000
Future FY	TBA

TOTAL ESTIMATED COST

DOE	$ 719,000

CUSTOMER SERVICE

800-553-7681

WEBSITE

www.netl.doe.gov

Background

One of the most critical research areas is aimed at monitoring the long-term storage stability and integrity of CO_2 in geologic formations. Research aimed at monitoring the integrity of CO_2 sequestered in geologic formations is certainly one of the most pressing areas of need if geologic sequestration is to become a significant factor in meeting this country's stated objectives to reduce greenhouse gas emissions. The most promising geologic formations currently under consideration for CO_2 sequestration are active and depleted oil and gas formations, brine formations, and deep, unmineable coal seams. Unfortunately, the long-term CO_2 storage capabilities of these formations are not well explored.

Primary Project Goal

The goal of this effort is to develop and demonstrate advanced monitoring techniques to assess the capacity, stability, rate of leakage, and permanence of CO_2 storage in geologic formations.

Objectives

- The primary objective is to evaluate a wide range of surface and near surface monitoring techniques that show promise in the detection of both the short term, rapid loss, and long-term, intermittent slow leakage of carbon dioxide from geologic formations.
- Monitor for carbon dioxide leakage at the West Pearl Queen Oil Field to ultimately determine the migration and fate of CO_2 after being injected into a depleted oil reservoir. Models and data developed will be used to predict physical and chemical changes in oil reservoir properties and the long-term storage capacity, safety, and integrity of oil reservoir sequestration.
- Monitor for carbon dioxide leakage at CO_2-ECBM/sequestration sites by conducting background studies of geophysical features, soil and atmosphere hydrocarbon patterns and concentrations, and monitoring locations and grid patterns for soil-gas sampling.
- Monitor with perfluorocarbon tracer compounds and evaluate tracer retention on coal.
- Perform geophysical site analysis from remote sensing and ground based measurements by combining satellite visible and infrared views with satellite radar and optical aerial photography.

Development of Comprehensive Monitoring Techniques to Verify the Integrity of Geologically Sequestered Carbon Dioxide

CONTACT POINTS

Curt White
Carbon Sequestration Science Focus Area Leader
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-5808
curt.white@netl.doe.gov

Arthur Wells
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-5975
arthur.wells@netl.doe.gov

Accomplishments

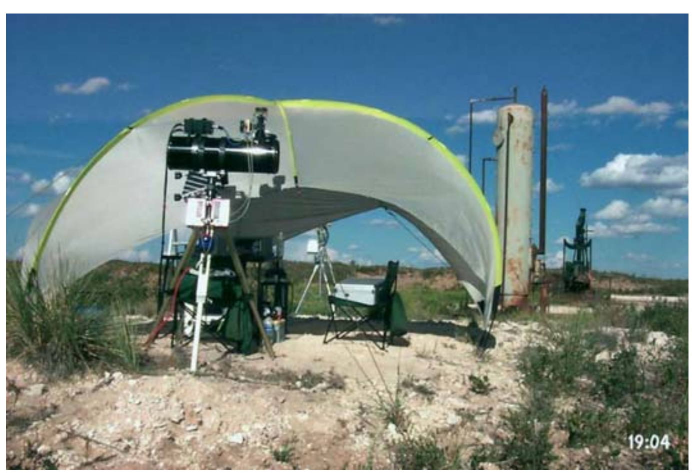
In previous years, work was completed on site selection for the initial field monitoring study. Agreements were made with various research agencies and state and federal environmental agencies to implement a monitoring program at the West Pearl Queen oil field site in southeast New Mexico where a carbon dioxide injection experiment will be conducted. An assessment of geological features at the New Mexico injection site was made from satellite images to aid in the placement of the chemical and optical monitors. Additionally, a contract was obtained for the services of the OPHIR Corp. to conduct a background survey of the atmospheric concentrations of CH_4, C_2H_6, and C_3H_8 at the injection well site, and surrounding area.

A group of novel tracer compounds was selected and the analytical protocol for their detection and quantification was decided upon.

A monitoring protocol was developed to maximize tracer detection. Techniques have been developed to sample soil gases for the tracers using an active gas sam-pling technique. A sampling pump was designed and several sampling systems were constructed at NETL. The protocol was evaluated at NETL prior to field-testing.

Benefits

Development of techniques to monitor the integrity of geologically sequestered CO_2 is needed to assure public health and safety and to gain public acceptance of geologic sequestration technology. Active and depleted oil and gas formations, brine formations, and deep coal seams that were previously unused now have the potential to serve as sinks for carbon dioxide sequestration. Additionally, by capturing carbon dioxide and sequestering it, harmful emissions into the atmosphere are prevented that may further increase global warming.



Spectroscopic Measurements – OPHIR Corp.
West Pearl Queen Field, New Mexico

Proj188.pmd

*Factsheets Under Development

Development of simulation tools for sequestration and retention of CO_2 in permeable media*
-NETL

Page left blank to accommodate 2-sided printing

PROJECT

facts

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

Sequestration

04/2004

NETL

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

John Litynski
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-1339
john.litynski@netl.doe.gov

Richard Benson
Los Alamos National Laboratory
528 35th St.
P.O. Box 1663
Los Alamos, NM 87544
505-665-0640

Applied Terrestrial Carbon Sequestration

Background

The key to any market-based carbon trading program that includes terrestrial sequestration is the ability to measure, across large and diverse areas, the quantity of carbon stored belowground in soils and aboveground in herbaceous plants and trees. Field data are needed to support carbon accounting, to monitor and verify carbon stocks, and to validate models of the carbon cycle for terrestrial systems. Therefore, the development and deployment of cost-effective measurement technologies is essential. The Applied Terrestrial Carbon Sequestration Project is addressing these needs with state-of-the-art technologies. The Project is producing cutting edge science and technology that will help reduce greenhouse gas (GHG) emissions, improve the productivity and sustainability of soils, and establish the scientific credibility required for a viable carbon measurement systems to support a carbon trading market.

Primary Project Goal

The primary project goal is to advance carbon measurement and monitoring technologies by developing a suite of robust and cost-effective technologies. The technologies under development include laser-induced breakdown spectroscopy (LIBS) to address the need to measure soil carbon and to be able to distinguish between organic and inorganic carbon. LIBS offers to provide a rapid, field-deployable, and cost-effective method for soil carbon determination. Another technology is microbial indicators to address the need to quickly and inexpensively assess the carbon status in soils when for example implementing new land management practices. A third technology is assessing the risks associated with terrestrial carbon inventories in lands under different management practices. Finally, another goal is to develop and implement methods to improve native plant growth/productivity and for the purpose carbon sequestration through improving vegetation on mine sites and other degraded lands.

The laser-induced breakdown spectroscopy (LIBS) units

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

Los Alamos National Laboratory (LANL)

COST

Total Project Value
$3,900,000

DOE/Non-DOE Share
$2,800,000/$1,100,000

Objectives

- To develop an integrated suite of technologies to measure, monitor, assess, and manage terrestrial carbon inventories.
- To increase analytical sensitivity, measurement accuracy, and precision of these technologies.
- To develop and test person-portable LIBS instruments.
- To develop LIBS calibration protocols independent of soil type.
- To address the need for a LIBS compatible bulk density measurement capability.
- To further develop microbes as early indicators of changes in soil carbon concentration to enable an early assessment of the effectiveness of land management practices for increasing soil organic carbon sequestration.
- To demonstrate field applications to mine sites, degraded lands, and rapid carbon cycling systems.
- To provide integrated technology for risk assessment of carbon management alternatives and uncertainties.

Accomplishments

- Designed and fabricated two field-portable LIBS units with multi-element analysis capability.
- Continued testing and benchmarking of field-portable LIBS units using core and discrete soil samples.
- Bench-tested and calibrated LIBS with over 1,000 soil samples.
- Obtained correlations between soil type and carbon calibration to develop robust calibration methods.
- Tested field-deployable LIBS at three sites.
- Designed and constructed two person-portable LIBS units for carbon soil analysis.
- Developed calibration curves for Raman detection of organic soil carbon
- Developed critical risk assessment metrics associated with plant available water, vegetation pattern and plant mortality.
- Demonstrated that soil microbes are sensitive, practical biological indicators of small annual increases in soil carbon concentrations.
- Developed industrial partner for soil microbial indicators; a phase one STTR proposal was submitted
- Refined method for improving revegetation/stabilization of semiarid mine land.
- Received R&D100 award for work on LIBS contribution to integrated measurement system called CARISS

Benefits

Concern over the potential for the buildup of GHGs in the atmosphere to contribute to global climate change has led the President to set a goal of reducing the amount of CO_2 emitted per dollar of GDP by 18% by 2012. A possible effective and low-cost method of contributing to the achievement of this goal is through the terrestrial sequestration of CO_2. However, this can only be achieved if we have effective measurement and analysis tools to verify carbon concentrations in a wide variety of environments. This project is working to provide these tools by meeting the need for (1) highly accurate portable measurement system(s), (2) effective and inexpensive bioindicators of changes in soil carbon and (3) advances in methods for assessing the risks associated with maintaining terrestrial carbon inventories. This integrated approach will provide a set of unique technologies and management tools required to address the GHG issue. An additional benefit of developing these technologies has been the advancement of mine-site revegetation/ stabilization methods.

Proj286.pmd

PROJECT facts

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

Sequestration

12/2004

Development of Science-based Permitting Guidance for Geologic Sequestration of CO_2 in Deep Saline Aquifers Based on Modeling and Risk Assessment

CONTACTS

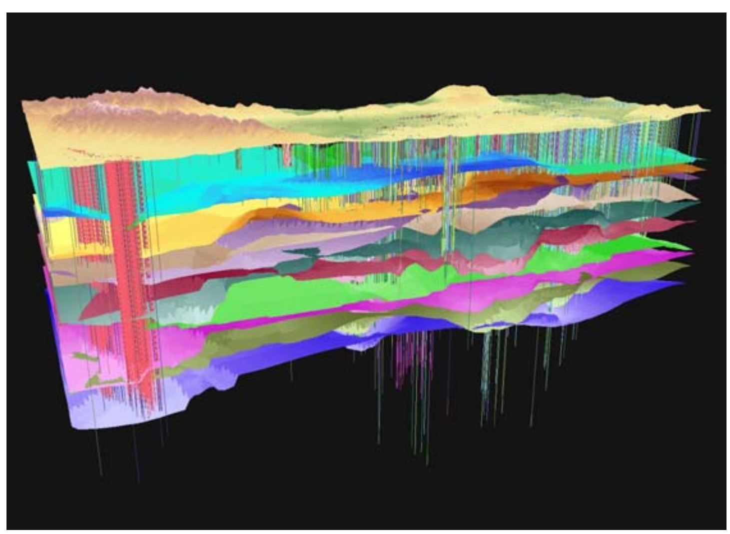
Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

David Hyman
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-6572
david.hyman@netl.doe.gov

Jean-Philippe Nicot
University of Texas at Austin
10100 Burnet Road, Building 130
Austin, TX 78713
jp.nicot@beg.utexas.edu
512-471-1534

Background

Geologic sequestration of CO_2 has been recognized as a potentially important way to mitigate the increase in the concentration of CO_2 in the atmosphere. However, if geologic sequestration is to become a reality, procedures to permit geologic sequestration projects must be put in place. Reasonable permitting practices are critical to stakeholders, because overly restrictive permitting could limit the use of geologic sequestration, while lax regulation could result in widespread public objections or negative consequences, should leaks occur. This study will focus on long-term (hundreds to thousands of years) sequestration of CO_2 in subsurface formations in the Texas Gulf Coast and Ohio/West Virginia areas. Not only are there large releases of CO_2 in these areas, but high-quality data are also available from pilot injection projects. This study will build on previous and ongoing studies related to CO_2 sequestration conducted by the Bureau of Economic Geology (BEG) and Pacific Northwest National Laboratory (PNNL). This comprehensive approach to geologic CO_2 sequestration should increase confidence in the applicability of this technology, which is critical for its success and for public acceptance.



Schematic for the concept of geological sequestration

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

University of Texas at Austin

Pacific Northwest National Laboratory

COST

Total Project Value
$240,154

DOE/Non-DOE Share
$179,921/$60,233

This study will develop guidelines for permitting CO_2 sequestration projects on the basis of a review of permitting procedures in other programs (e.g., deep-well injection, gas storage systems, and high-level radioactive waste disposal), results of research programs on CO_2 sequestration and related projects, reservoir modeling, and risk assessment. CO_2 sequestration is an emerging field in which new results are being produced rapidly; therefore, it is critical to conduct a thorough search of the literature and to analyze the applicability of reported results to permitting issues. The modeling effort will build on modeling studies of the pilot CO_2 injection study in the Texas Gulf Coast conducted by Lawrence Berkeley National Laboratory (LBNL) in collaboration with the BEG. Sensitivity analyses will help identify critical issues and delineate potential leakage pathways. A risk assessment will extend the reservoir simulation results to aquifers, soil, biota, the atmosphere, and surface-waters. The results of these analyses will provide input needed to develop permitting protocols that will provide operators, regulators, and the public with increased confidence that the permitting process will ensure the selection of safe, optimal sites for CO_2 sequestration.

Primary Project Goal

The primary project goal is to develop a guidance document that addresses permitting issues relative to the geologic sequestration of CO_2, including specific recommendations for developing a permitting protocol. This can provide decision makers with a reasonable estimate of the potential future performance of a disposal system and a clearer understanding of how uncertainties affect that estimate.

Objectives

- To develop science-based permitting guidance.
- To perform reservoir and seal modeling.
- To perform risk and consequences assessments.
- To determine the implications of permitting.

Benefits

There is growing concern among climate scientists that the buildup of greenhouse gases, particularly CO_2, in the atmosphere is leading to global warming with potentially serious consequences. This may result in the need to reduce the amount of CO_2 emitted to the atmosphere. One promising technique for accomplishing this is the capture of CO_2 from large point sources, such as power plants, followed by sequestration in geologic formations. However, sequestration projects will not be possible until permitting protocols are in place. This project will develop science-based guidelines that can help government officials develop the required permitting procedures.

Proj318.pmd

***Factsheet Under Development**

Stored CO_2 & Methane Leakage Task Assessment and Monitoring Tool Development: CO_2 Capture Project Phase 2*
- BP Corporation North America Inc.

Page left blank to accommodate 2-sided printing

PROJECT facts

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

Sequestration

03/2005

Assessing Fossil and Recent Carbon Pools in Reclaimed Mined Soils

CONTACTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

John Litynski
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-1339
john.litynski@netl.doe.gov

Rattan Lal
Principal Investigator
The Ohio State University Reserach Foundation
210 Kottman Hall
School of Natural Resources
Columbus, OH 43210
614-292-9069
lal.1@osu.edu

Background

There is ample indication that reclaimed mine lands have great capacity to sequester carbon. This carbon could offset CO_2 emissions associated with extraction and burning of coal and provide public utilities and other industries with carbon credits. However, at the present time, estimates of carbon pools in reclaimed mined lands are uncertain. This uncertainty is primarily linked to failure to account for carbon associated with coal particles and, given the variability of soil properties at reclaimed land sites, lack of standardized sampling protocols in assessing carbon pools.

Organic carbon present in mined lands is a mixture of carbon from coal particles (old carbon) and carbon resulting from decomposition of plant residues (recent carbon). In these soils, carbon sequestration essentially refers to the increase in the new carbon pool. However, because of their high carbon content, coal particles represent a large carbon background against which detection of small increases in recent C are difficult to determine. This is an analytical challenge that needs to be resolved in order to generate credible information on carbon sequestration rates in reclaimed mined lands.

In nature, carbon occurs as stable isotopes ^{12}C and ^{13}C (1.12% of atmospheric CO_2) and as the radioisotope ^{14}C (half-life of 5,730 years). Given that coal was deposited several hundred million years ago, coal shows no radiocarbon activity. Thus, ^{14}C activity recorded in soil samples from reclaimed mined lands can be attributed to new carbon. Although this approach has been successfully used in assessing the contribution of lignite to carbon pools in reclaimed lands, high cost precludes widespread adoption of this technique. In this study, radiocarbon activity will only be used to validate the proposed chemo-thermal and ^{13}C -based procedures. The ^{13}C approach exploits differences in ^{13}C composition between coal and new carbon that is the result of the decomposition of plant residues (e.g., corn), making it possible to partition the total carbon pool in reclaimed soils into coal carbon and recent carbon. The chemo-thermal procedure assumes that coal carbon is less reactive than recent carbon. Therefore, a series of chemical and thermal treatments will be applied to selectively remove the new carbon from the sample so that the refractory coal carbon left behind can be quantified.

This project will include mining sites, reclaimed cropland with a recent corn crop, and reclaimed grassland at various locations across a 300-400 km transect spanning the Northern Appalachian coal basin in Ohio, West Virginia, and Pennsylvania. Topography- and grid-based soil sampling will be conducted at selected reclaimed grassland sites, and through assessment of the spatial patterns of carbon distribution, a sampling design will be proposed to better estimate carbon in reclaimed mined lands.

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNER

The Ohio State University Reserach Foundation

COST

Total Project Value
$551,719

DOE/Non-DOE Share
$425,532/$126,187

Primary Project Goal

The primary goal of this project is to develop and test several analytical procedures that can determine the amount of coal-derived C in reclaimed mined lands.

Coal mined lands in southeastern Ohio

Objectives

The objectives of this project are:

- To develop and test a ^{13}C-based procedure to determine the fraction of coal carbon present in reclaimed soils.
- To evaluate a chemo-thermal procedure, based on the lower reactivity of coal carbon compared to recent carbon, to partition organic carbon in reclaimed soils into coal-derived and newly-deposited carbon fractions.
- To establish an optimum sampling protocol (intervals and number of sampling points) to produce an accurate assessment of carbon sequestration in reclaimed mined lands.

Accomplishments

- Two chemical methods were modified and tested for selective removal of recent Carbon in minesoils:
  - NaOH extraction
  - Acidified $K_2Cr_2O_7$ oxidation
- Soil coal mixture analysis indicated that both methods were effective in removing recent C with little effect on coal C.
- Dichromate oxidation removed greater percentage of organic matter from coal-soil mixture than NaOH-extraction-combustion method.
- Estimated coal C in minesoils ranged from 4 to 67% of soil organic carbon (SOC), showing the necessity of having methods to differentiate old and new carbon pools.

Benefits

One option for sequestering CO_2 is by increasing the amount of carbon stored in reclaimed mined lands. However, to allow credit for such sequestration there must be methods to verify the increased carbon content of the soil. That is, there must be analytical techniques which can accurately determine recent carbon. A major problem, however, is the presence of coal carbon, which greatly increases the difficulty of accurately determining recent carbon. By addressing this problem, this project will make a significant contribution to determining the viability and the potential of carbon sequestration in reclaimed mined land to reducing greenhouse gas emissions in the United States.

PROJECT **facts**

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

Sequestration

03/2005

Low Cost Open-Path Instrument for Monitoring Atmospheric Carbon Dioxide at Sequestration Sites

CONTACTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

José D. Figueroa
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4966
jose.figueroa@netl.doe.gov

William A. Goddard III
Principal Investigator
California Institute of Technology
1200 E. California Blvd.
M/C 139-74
Pasadena, CA 91125
626-395-2731
wag@wag.caltech.edu

Background

Growing concern over the effect of the buildup of greenhouse gases (GHG), particularly carbon dioxide, in the atmosphere on global climate may lead to the curtailment of CO_2 emissions. One potential course of action by industry to reduce GHG emissions is the subsurface disposal of carbon dioxide. An important requirement of such disposal is verification that the injected gases remain in place and do not leak to the surface.

Perhaps the most direct evidence of a successful sequestration project is the lack of a detectable CO_2 concentration above the background level in the air near the ground. Although measurement of CO_2 concentration can be performed, it is difficult to accomplish at a reasonable cost over the large area that is typical of large subsurface gas injection projects. One technically attractive approach is to employ a so-called open-path device that uses a laser to shine a beam, with a wavelength that CO_2 absorbs, over many meters. The attenuated beam reflects from a mirror and returns to the instrument for determination of the CO_2 concentration. One instrument can sample a large area, if it can reflect from more than one mirror.

Current commercial instruments capable of this cost tens of thousands of dollars. The purpose of this project is to develop an inexpensive (instrument cost of no more than a few hundred dollars) open-path laser instrument to measure carbon dioxide concentration over the range of interest (300–500 ppmv). The low cost target should be attainable by designing an instrument for this one specific application. In contrast, the expensive commercial units can measure the levels of multiple gases over a wider range of concentrations. The newest technology in the communications industry can be used to build a prototype with inexpensive, off-the-shelf components.

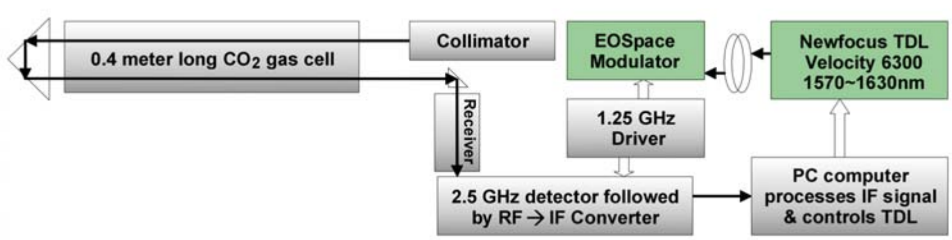


Figure 1. Schematic for bench top CO_2 measurement using FM spectroscopy

Primary Project Goal

The primary goal is to develop and test an inexpensive open-path instrument that will measure and monitor atmospheric CO_2 concentrations within a range of 300-500 ppmv.

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNER

California Institute of Technology

COST

Total Project Value
$207,158

DOE/Non-DOE Share
$165,726/$41,432

Objectives

The objectives of the project are:

- To develop a prototype instrument capable of measuring CO_2 concentration over a five kilometer path length with an update speed of once every several minutes and an accuracy of 98-99%.
- To test the prototype instrument over a short range (e.g., 100 m) and determine its performance range.
- To mount the prototype instrument on a rooftop and determine its performance over a range up to 5 km.
- To field test the monitor in an operating CO_2 geological site.
- To develop a computer simulation of system availability.

Benefits

One approach that is being seriously considered for alleviating the buildup of GHGs in the atmosphere is the capture of CO_2 from fossil fuel fired power plants and sequestering the CO_2 in geologic formations. Although this approach appears to be technically feasible, it will not be accepted by the public unless they can be assured that the sequestered CO_2 will remain in place and not leak to the surface. A vital part of providing this assurance is the ability to economically measure CO_2 concentrations over large areas so that any leaks can be quickly detected and remediation measures taken. The success of this project will go a long way toward providing an instrument to fill this monitoring need.

Breakthrough Concepts

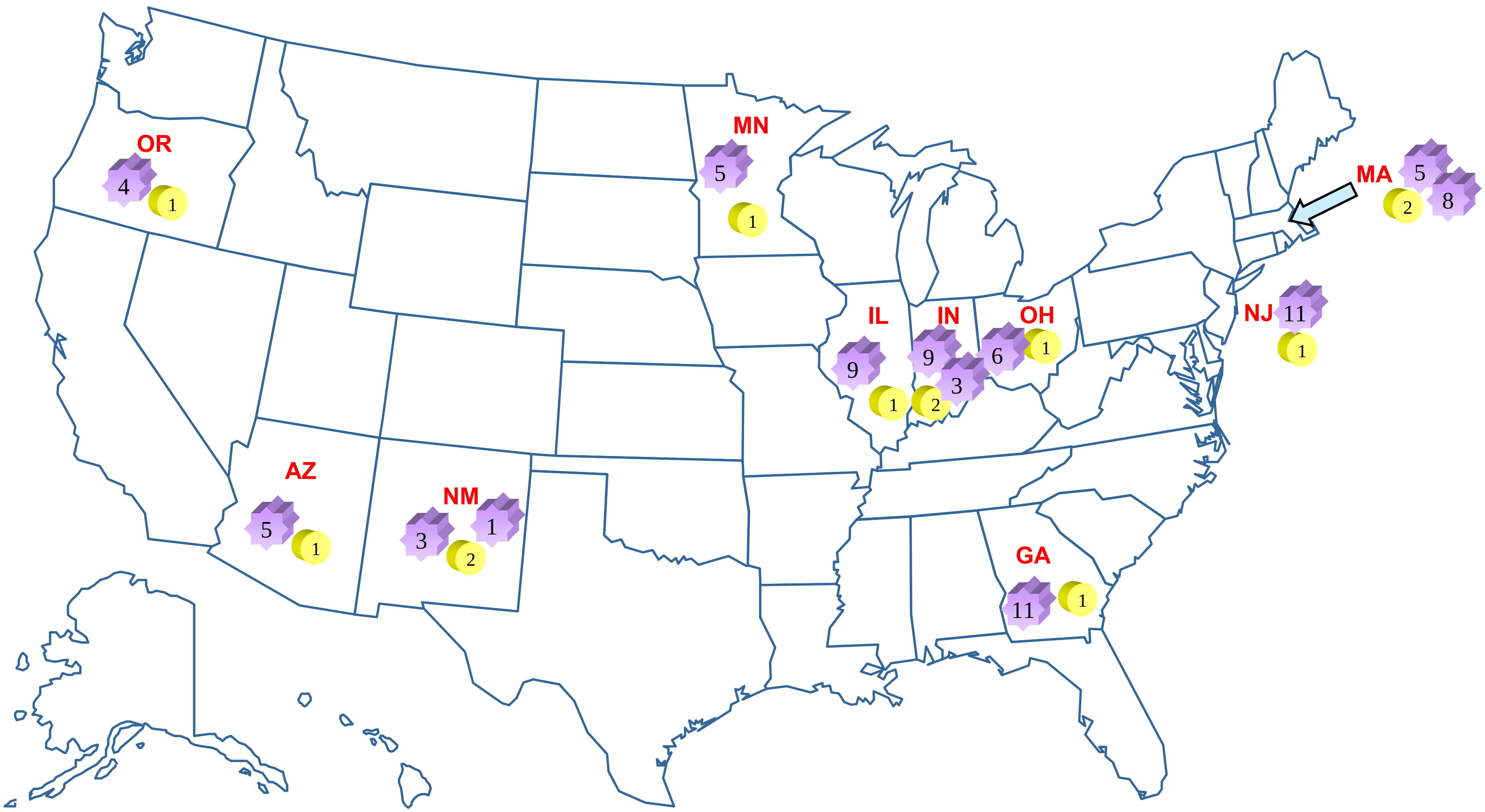
Page left blank to accommodate 2-sided printing

Breakthrough Projects

LEGEND

Number of Breakthrough Projects

Congressional District



Doesn't include NETL Projects

Project Title	Primary Contractor	Congressional District
Recovery & Sequestration of CO_2 from Stationary Comb. Systems by Photosynthesis of Microalgae	Physical Sciences, Inc.	MN05
Enhanced Practical Photosynthetic CO_2 Mitigation	Ohio University	OH06
CO_2 Mineralization	Albany Research Center	OR04
Advanced CO_2 Cycle Power Generation	Foster Wheeler	NJ11
Mineral Sequestration of CO_2 - Chemical Dissolution Approaches	LANL	NM03
A New Concept for the Fabrication of Hydrogen Selective Silica Membranes	University of Minnesota	MN05
Novel Dual Functional Membrane for Controlling Carbon Dioxide emissions from Fossil Fueled Power Plants	University of New Mexico	NM01
Carbon Dioxide Separation with Novel Microporous Metal Organic Frameworks	UOP L.L.C	IL09
Design and Evaluation of Ionic Liquids as Novel Absorbents	University of Notre Dame	IN03
Neutralizing Carbonic Acid in Deep Carbonate Strata Below the North Atlantic	Harvard University	MA08
A Novel Approach To Mineral Carbonation: Enhancing Carbonation While Avoiding Mineral Pretreatment Process Cost	Arizona State University	AZ05
A Novel Approach to Experimental Studies of Mineral Dissolution Kinetics	Indiana University	IN09
Process Design for the Biocatalysis of Value-Added Chemicals from CO_2	University of Georgia Research Foundation	GA11

Breakthrough Concepts

Technology Target

- Pursuing revolutionary and transformational sequestration approaches
- Potential for low cost, permanence, and large global capacity

Advanced CO_2 Capture

Univ Minnesota – Silica membrane

Univ New Mexico – Dual function membrane for CO_2 separation and removal

Univ. Notre Dame – Ionic liquids

UOP – Microporous metal organic frameworks for CO_2 capture

Foster Wheeler – Advanced CO_2 cycle

Advanced Sequestration
Advanced Geochemical & Subsurface Technology

Harvard – Carbonate sediments below sea floor

Arizona State – Mineral carbonation

ARC – Mineral Carbonation

LANL – Mineral sequestration

Indiana Univ. – Mineral dissolution kinetics

Novel Niches

Univ of Georgia – Microbial CO_2 conversion

Physical Science – CO_2 sequestration via photosynthesis of microalgae

Ohio Univ. – Photosynthetic CO_2 mitigation

NETL

Project Title	Primary Contractor	Fact Sheet Listing
Recovery & Sequestration of CO_2 from Stationary Comb. Systems by Photosynthesis of Microalgae	Physical Sciences, Inc.	B-5
Enhanced Practical Photosynthetic CO_2 Mitigation	Ohio University	B-7
CO_2 Sequestration By Mineral Carbonation Using A Continuous Flow Reactor	Albany Research Center	B-9
Advanced CO_2 Cycle Power Generation	Foster Wheeler	B-11
Mineral Sequestration of CO_2 - Chemical Dissolution Approaches*	LANL	B-13
A New Concept for the Fabrication of Hydrogen Selective Silica Membranes	University of Minnesota	B-15
Novel Dual Functional Membrane for Controlling Carbon Dioxide emissions from Fossil Fueled Power Plants	University of New Mexico	B-17
Carbon Dioxide Separation with Novel Microporous Metal Organic Frameworks	UOP L.L.C.	B-19
Design and Evaluation of Ionic Liquids as Novel Absorbents	University of Notre Dame	B-21
Neutralizing Carbonic Acid in Deep Carbonate Strata Below the North Atlantic	Harvard University	B-23
A Novel Approach To Mineral Carbonation: Enhancing Carbonation While Avoiding Mineral Pretreatment Process Cost	Arizona State University	B-25
A Novel Approach to Experimental Studies of Mineral Dissolution Kinetics	Indiana University	B-27
Process Design for the Biocatalysis of Value-Added Chemicals from CO_2	University of Georgia Research Foundation	B-29

* Factsheet Under Development

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

01/2004

RECOVERY & SEQUESTRATION OF CO_2 FROM STATIONARY COMBUSTION SYSTEMS BY PHOTOSYNTHESIS OF MICROALGAE

CONTACT POINTS

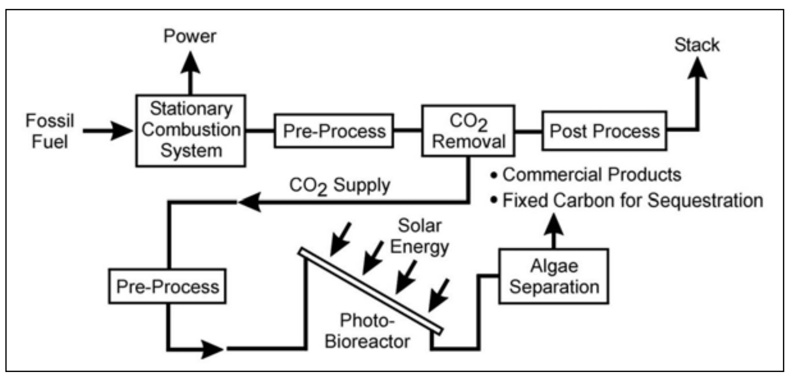
Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Heino Beckert
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-4132
heino.beckert@netl.doe.gov

Takashi Nakamura
Principal investigator
Physical Sciences, Inc.
20 New England Business Court
Andover, MA 01810
925-743-1110
nakamura@psicorp.com

Background

Most anthropogenic carbon dioxide (CO_2) emissions result from the combustion of fossil fuels for energy production. Photosynthesis has long been recognized as a means, at least in theory, to sequester anthropogenic CO_2. Aquatic microalgae have been identified as fast growing species whose carbon fixing rates are higher than those of land-based plants by one order of magnitude. A large-scale photobioreactor would be similar to a large display of solar panels, except instead of producing electricity, the solar energy would serve though photosynthesis by microalgae to convert CO_2 from fossil fuel combustion to stable carbon compounds for sequestration. Some high-value products would also be produced to offset the carbon sequestration cost.



Recovery and sequestration of CO_2 from stationary combustion systems by photosynthesis of microalgae

An ideal methodology for photosynthetic sequestration of anthropogenic carbon dioxide has the following characteristics: (1) a high rate of CO_2 uptake, mineralization of CO_2, (2) resulting in permanently sequestered carbon, (3) produce revenue from sale of high value products, and (4) use of concentrated, anthropogenic CO_2 before it enters the atmosphere. In this research program, Physical Sciences Inc. (PSI), Aquasearch, and the Hawaii Natural Energy Institute at the University of Hawaii are jointly developing technology for the recovery and sequestration of CO_2 from stationary combustion systems by photosynthesis of microalgae. The research is aimed primarily at quantifying the efficacy of microalgae-based carbon sequestration at an industrial scale. The principal research activities will be focused on demonstrating the ability of selected species of microalgae to effectively fix carbon from typical power plant exhaust gases. The results will be used to evaluate the technical efficacy and associated economic performance of large-scale photobioreactor carbon sequestration facilities.

CUSTOMER SERVICE

800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

Physical Sciences, Inc.
University of Hawaii
Aquasearch

COST

Total Project Value:
$2,361,111

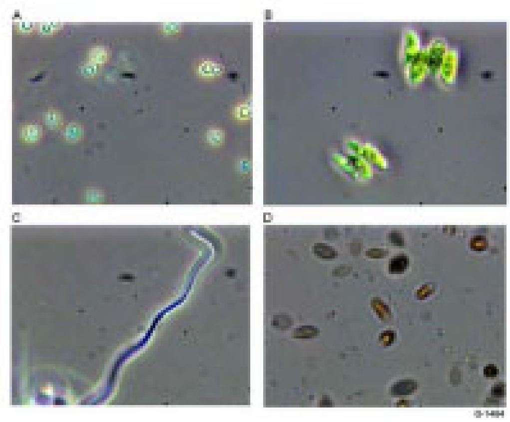
DOE/Non-DOE Share:
$1,682,028 / $679,083

Primary Project Goal

The primary project goal is to develop technologies pertaining to: (1) treatment of effluent gases from fossil fuel combustion systems; (2) transferring CO_2 into aquatic media; and (3) converting CO_2 efficiently by photosynthetic reactions to materials to be reused or sequestered.

Objectives

- Determined the effect of process variables on the production of various strains of microalgae
- Optimize and demonstrate an industrial-scale photobioreactor
- Perform economic analyses of commercial-scale microalgal CO_2 sequestration technology



Microphotographs of four types of algal cells at a magnification of 400x showing differences in size and morphology

Accomplishments

Tested 50 strains of microalgae for growth at different temperatures; analyzed 34 strains for high-value pigments; tested 21 strains for tolerances to simulated flue gases; and tested 28 strains for potential carbon sequestration into carbonates for long-term storage. Tested CO_2 removal process, CO_2 injection device, process control devices, and algae separation process for scaled-up photobioreactor.

PSI delivered its coal reactor to Aquasearch. Aquasearch and PSI prepared work on direct feeding of coal combustion gas to microalgae. Aquasearch started their effort on economic analyses of commercial scale photobioreactor. University of Hawaii continued effort on system optimization of the CO_2 sequestration system.

Benefits

This project represents a radical departure from the large body of science and engineering in the area of gas separation. This research has significant potential to create scientific and engineering breakthroughs for the operation of controlled, high-throughput, photosynthetic carbon sequestration systems. This type of system will reduce carbon dioxide emissions generated by fossil fueled power plants. The microalgae used and grown in this process can produce high-value pharmaceuticals, fine chemicals, and commodities. Revenues from the sale of these products can help offset carbon sequestration costs.

Proj245.pmd

PROJECT facts

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

Sequestration

09/2004

Enhanced Practical Photosynthetic CO_2 Mitigation

CONTACT POINTS

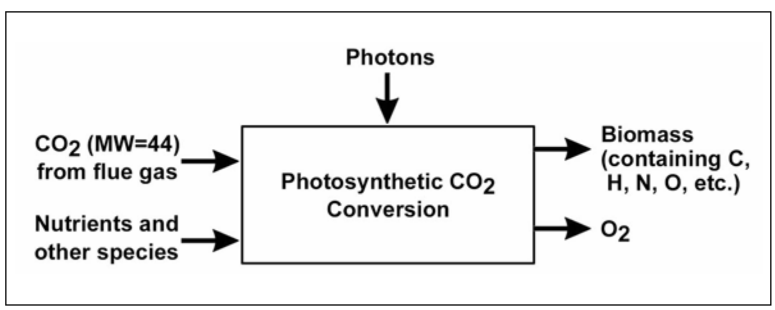
Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Heino Beckert
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-4132
heino.beckert@netl.doe.gov

David Bayless
Ohio University
Athens, OH 45701
740-593-0264
bayless@ohio.edu

Background

Biological carbon sequestration, in particular engineered photosynthesis systems, offers advantages as a viable near-to-intermediate term solution for reduced carbon emissions in the energy sector. Photosynthetic (or "natural" sequestration) systems produce usable by-products (biomass). Further, such systems could minimize capital and operating costs, complexity, and energy required to transport CO_2 that challenge sequestration in deep aquifers or mines. Lower capital costs are extremely important, especially to small generators, who may not be able to afford separation and CO_2 delivery systems that are only cost effective if done on very large scales. For coal to remain competitive, especially in the rapidly emerging distributed generation market (< 50 MW), and to ensure future fuel diversification, a portfolio of viable and practical sequestration techniques will have to be developed. Photosynthetic systems should be a part of that portfolio. The concept behind engineered photosynthesis systems is straightforward. Even though CO_2 is a fairly stable molecule, it is the basis for the formation of complex sugars by green plants through photosynthesis. The relatively high content of CO_2 in flue gas (approximately 14% compared to 350 ppm in ambient air) has been shown to significantly increase growth rates of certain species of microalgae. Therefore, application is ideal for contained systems, engineered to use specially selected strains of microalgae to maximize CO_2 conversion to biomass, absorbing greenhouse gases. In this case, the microalgal biomass represents a natural sink for carbon.



Simple diagram of the photosynthetic conversion process of CO_2 to biomass and oxygen

CUSTOMER SERVICE

800-553-7681

WEBSITE

www.netl.doe.gov

PARTNER

Ohio University

COST

Total Project Value:
$1,369,495

DOE/Non-DOE Share:
$1,075,022 / $294,473

Primary Project Goal

The main purpose of this research is to demonstrate and optimize low-risk methods of CO_2 mitigation based on existing biological organisms capable of significant CO_2 uptake and offer a valid near-term solution for the CO_2 sequestration problem.

Objectives

The project will demonstrate the technical and economic feasibility of using an 'optimized' enhanced photosynthesis system that (a) separates and uses various spectral regions of direct, non-diffuse sunlight to maximize cyanobacteria growth, (b) directly decreases CO_2 concentrations in the emissions of fossil generation units, (c) reduce the required space needed (compared to other biological techniques) by an approximate factor of 25, and (d) simultaneously produce enough electrical energy to nearly self-power the entire sequestration system.

Accomplishments

- Isolated 15 unialgal cultures that show promise for growth on an artificial substrate inside a photobioreactor
- Established positive effect of Ca^{+2} on algal growth rate on artificial substrate (Omnisil screens)
- Installed a solar light collector, fiber optic light cables and light distribution panels for the photobioreactor
- Tested and improved the Photobioreactor design for evaluation of large-scale biofilm placement
- Filed a patent claim titled, "Enhanced Practical Photosynthetic CO_2 Mitigation," which is about the bioreactor design and how to use it to control CO_2

Benefits

Three major benefits, in addition to CO_2 mitigation, could result from the use of this novel method of photosynthetic sequestration. The production of oxygen would be one benefit. Oxygen is a natural product of photosynthesis. The second benefit of this project would be the reduction of gaseous pollutants including potential NH_3 slip (from selective catalytic reduction to control NO_X) and NO_X, In terms of other pollution control, this process could provide NO_X control at no additional cost. First, the flow process used to enhance soluble carbon concentration is a natural scrubber. Not only is NO_X converted to nitrates, SO_X is converted to sulfates and sulfites, and any NH_3 that might slip through an upstream SCR process for NO_X reduction will be scrubbed as well. Both NO_X and NH_3 scrubbing are not only an additional benefit; such scrubbing is beneficial to photosynthesis, as the microalgae require nitrogen to grow. The third benefit would be from the production of biomass with beneficial end-uses. The resulting biomass has numerous beneficial uses. In addition to being a potential fuel, microalgae have been used as soil stabilizers, fertilizers, in the generation of biofuels, such as biodiesel and ethanol, and to produce H_2 for fuel cells. In recent tests, it also has shown suitable ignition characteristics to be co-fired with coal in pulverized coal-fired generation units.

Proj246.pmd

P R O J E C T
facts

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

Sequestration

01/2005

NETL

CO_2 SEQUESTRATION BY MINERAL CARBONATION USING A CONTINUOUS FLOW REACTOR

Background

Advanced chemical processing may lead to unique sequestration technologies or to improvements in our understanding of the chemistry involved that will enhance the performance of other sequestration approaches. CO_2 mineralization is the most permanent method for storing CO_2. This approach exploits a carbonation reaction that combines CO_2 with alkaline earth elements (predominantly magnesium, but also iron and calcium) derived from silicates to yield thermodynamically stable solid mineral carbonates. Sufficient alkaline earth silicates exist to dispose of all the CO_2 that could be produced from the world's entire reserves of conventional fossil fuels. CO_2 mineralization mimics natural chemical cycles involving CO_2. Nature has already sequestered approximately 40,000,000 Gt of carbon in the form of mineral carbonates, mostly as $CaCO_3$. These carbonates formed primarily as a result of weathering, in which calcium silicates are altered by carbonic acid in rainwater, releasing calcium ions to rivers and the ocean where carbonates are formed. This process is one of the primary components of the natural carbon cycle. Unfortunately, the natural carbon cycle operates on a time scale too long to accommodate the rapid rate of anthropogenic CO_2 emissions from the use of fossil fuels.

The Albany Research Center (ARC) is working on the development of a continuous flow reactor for the mineral carbonization process. The process has been demonstrated in batch, laboratory-scale reactors over a wide range of conditions, but a continuous flow process is necessary for economic viability. Basically, this process will operate at a relatively high temperature (185ºC) and pressure (2,300 psi) and inject supercritical CO_2 using intense mixing into finely ground minerals held in aqueous suspension to produce stable carbonated minerals. The best reactants identified for carbonation are the magnesium-containing minerals olivine and serpentine. Both minerals show a relatively high reactivity with CO_2, produce readily filterable product slurries, generate products that have good long-term stability, and have wide distribution in sufficient quantities to be good candidates for regional implementation of CO_2 sequestration.

TURNING CO_2 TO MINERALS - Gaseous carbon dioxide can be captured and converted into these environmentally-safe, magnesite minerals. The brown mineral is produced when olivine is used in the reaction; the white powder is produced when serpintine is used.

CONTACTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Philip Goldberg
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-5806
Philip.goldberg@netl.doe.gov

Richard Walters
Albany Research Center
U.S. Department of Energy
1450 Queen Ave. SW
Albany, OR 97321-2198
541-967-5873
walters@alrc.doe.gov

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

Albany Research Center (ALRC)

Arizona State University

Los Alamos National Laboratory

Science Applications International Corporation

COST

Total Project Value
$1,419,100

DOE/Non-DOE Share
$1,419,100/ $0

Primary Project Goal

The primary goal of the proposed research is to develop an economically and environmentally acceptable integrated mineral carbonation process for disposal of CO_2 generated by the combustion of fossil fuels in power-generation plants.

Objectives

Laboratory-Scale Continuous Flow Reactor

- Determine the engineering parametrics
- Incorporate optimized process variables into the reactor testing
- Initiate study for integration of pre- and post-treatment steps with flow reactor design
- Complete detailed material and energy balances for the flow reactor system.
- Assist in the completion of an updated cost evaluation of the Carbonation Process using the flow reactor concept
- Demonstrate process integration or pre- and post-treatment steps in the flow reactor system
- Continue studies on slurry separation and recycle issues

Fundamental Studies

- Finalize slurry density and pH investigations, determining optimum solids content and system pH
- Determine effective solution and solids recycle potential
- Complete the study on the activated, pseudo-amorphous mineral phase
- Identify optimum parametric space for pretreated mineral reactant
- Determine energy requirements for favored mineral pretreatment options

Accomplishments

The process has been demonstrated in batch-type laboratory-scale tests over a wide range of temperatures and partial pressures of CO_2. Over 80% of the reaction can now be completed with in an hour. Research to date has advanced the understanding of the kinetics and important parameters of the reaction, but the development of a continuous reactor is necessary to prove the process on a larger scale. Researchers hope to move from 5 pounds per hour of minerals being processed to 500 pounds per hour and ultimately to 10 tons per hour.

Benefits

The major benefits of CO_2 sequestration by mineral carbonation are:

Long Term Stability - Mineral carbonation is a natural process that is known to produce environmentally safe and stable material over geological time frames. The production of mineral carbonates insures a permanent fixation rather than temporary storage of the CO_2, thereby guaranteeing no legacy issues for future generations.

Vast Capacity - Raw materials for binding the CO_2 exist in vast quantities across the globe. Readily accessible deposits exist in quantities that far exceed even the most of coal reserves.

Potential to be Economically Viable - The overall process is exothermic and, hence, has the potential to be economically viable. In addition, its potential to produce value-added by-products during the carbonation process may further compensate its costs.

Project 323.pmd

P R O J E C T
facts

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

Sequestration

07/2004

Advanced CO_2 Cycle Power Generation

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

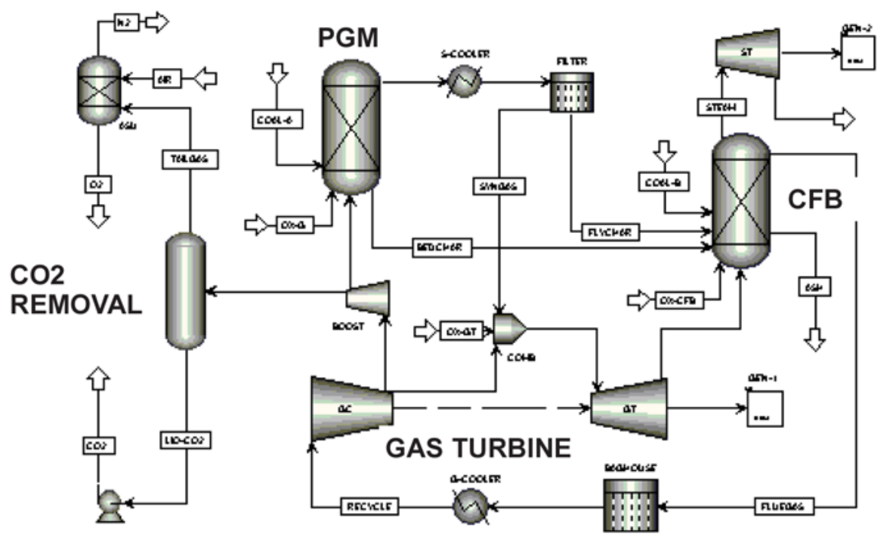
Timothy Fout
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880
304-285-1341
timothy.fout@netl.doe.gov

Aydemir Nehrozoglu
Foster Wheeler North America Corp.
12 Peach Tree Hill Road
Livingston, NJ 07039
973-535-2541

Background

This project will develop a conceptual power plant design based on hybrid fluidized bed technology that can achieve 100% CO_2 capture while avoiding the cost and technical limitations of CO_2 separation from syngas. The plant utilizes the novel concept of using CO_2 as a working fluid within a coal gasification-based power plant, which efficiently generates power while concentrating CO_2 for sequestration.

The first step of the process is air separation, where oxygen is extracted from air for use in both the gasification and combustion processes. Oxygen reacts with coal and steam in a partial gasification module (PGM) to generate syngas and char residue. Both of these fuel streams are then burned with oxygen: The syngas is burned in the combustion turbine to drive a gas turbine generator, and the char is burned in a CFB steam generator to make steam for the steam cycle.



The CO_2 is concentrated in the process by recycling the exhaust gas flow, consisting primarily of CO_2, between the CFB combustor and the combustion turbine. As the final step to balance the process, a portion of the pressurized CO_2 rich gas is diverted from the process for sequestration. There is no plant stack and all waste streams including CO_2 from the process are in their most concentrated and manageable form.

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

Foster Wheeler North America Corp.

COST

Total Project Value:

$300,000

DOE/Non-DOE Share:

$240,000/$60,000

Primary Project Goal

The main goal is to develop an advanced, gasification-based power cycle that produces a concentrated CO_2 stream for sequestration while achieving high plant efficiency and reliability at a competitive cost.

Objectives

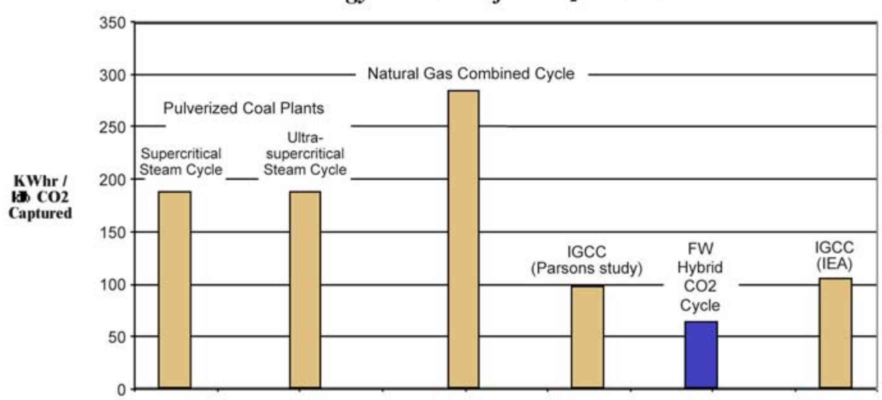
The objectives are to optimize the plant process, complete a conceptual design of the plant, and estimate plant capital and operating cost to assess the feasibility of this advanced power technology.

Accomplishments

Energy Consumed for CO_2 Removal

The plant conceptual design, a detailed thermodynamic cycle analysis, and the design of the gasifier and char combustor were completed. The results of the project to date show that the Foster Wheeler CO_2 hybrid cycle can sequester CO_2 with greater efficiency than other leading sequestration concepts, including IGCC with CO_2 separation.

Energy Consumed for CO_2 Removal



Benefits

This technology offers the following key benefits:

- A completely zero emissions stockless plant that can produce power and a high pressure CO_2 exhaust stream more efficiently than conventional gasification technologies.
- CO_2 sequestration is achieved while avoiding the costly, energy-intensive CO shifting, CO_2 chemical/physical absorption, and CO_2 stripping processes used in conventional gasification technology.
- A wide range of inexpensive coals can be used as fuel because fluidized bed technology is used for both the gasification and combustion processes.
- Minimal water is used in the process because water scrubbing and water gas shift processes are avoided.
- All effluent streams from the process (SO_2, CO_2, NOx, N_2, H_2O, metals, ash) are concentrated for efficient reuse or disposal.
- The CO_2 exhaust stream is provided inherently at pressure from the process.
- It is a simplified process offering higher reliability and lower plant cost.

Proj283.pmd

*Factsheet Under Development

Mineral Sequestration of CO_2 - Chemical Dissolution Approaches*
-LANL

Page left blank to accommodate 2-sided printing

PROJECT facts

Sequestration

08/2004

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

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

David A. Lang
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4881
david.lang@netl.doe.gov

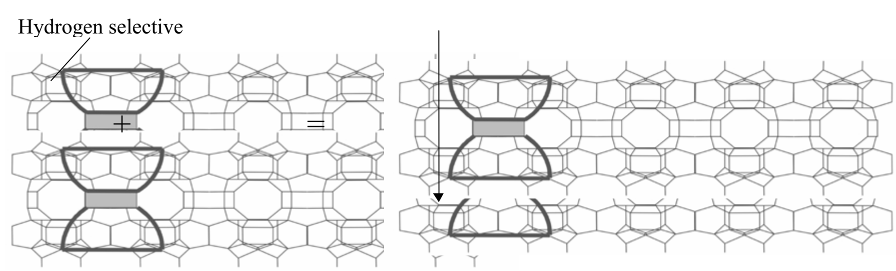
Michael Tsapatsis
University of Minnesota
Department of Chemical Engineering and Materials Science
151 Amundson Hall
421 Washington Avenue SE
Minneapolis, MN 55455
612-626-0920
tsapatsi@cems.umn.edu

A New Concept for the Fabrication of Hydrogen Selective Silica Membranes

Background

As stated in the NRC report on Novel Approaches to Carbon Management, there is a need for a novel membrane that can achieve the separation of CO_2 and H_2 at a high temperature and pressure. Extensive efforts over the last several decades have explored high temperature H_2-selective membranes made of SiO_2 and other oxides; Pd and other metals or alloys; and, more recently, various zeolites and non-aluminosilicate molecular sieves. Although promising separation results have been reported for many of these technologies, they all suffer from high production costs for membrane fabrication and long term stability problems. This project revisits the objective of high temperature H_2-selective membranes with a fresh look. It explores a new concept for the fabrication of ultrathin, hydrothermally stable, molecular sieve, H_2-selective membranes.

The concept is based on the use of crystalline layered silicates that are often encountered as by-products in the synthesis of, and in some cases are "precursors" to, high silica zeolites. Several of the currently known high silica layered materials are made up of microporous layers that may contain pores running within the layers but with no open microporosity perpendicular to the layers. The largest pore openings in the direction perpendicular to the layers are 6-membered-ring openings, i.e. rings of 6 interconnected SiO_4 tetrahedra. These ultra-small pore openings are ideal for H_2 molecular sieving membranes.



Condensation of silicate layers leads to a zeolite by elimination of water and formation of Si-O-Si linkages between the layers. In this view, large pores are evident however in the direction indicated by the arrow transport is limited by pores that will allow permeation of hydrogen but not of carbon dioxide. The dangling bonds at the end of the layers represent Si-OH while the lines represent Si-O-Si.

The fabrication method consists of the synthesis of ordered layered silicates, preparation of thin plate-like particles from these layered silicates, and deposition of the particles using layer-by-layer assembly followed by calcination. The membranes will be tested for H_2 separation from CO_2 at high temperature and pressure and tested for thermal stability at high temperature and pressure in the presence of water vapor.

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

University of Minnesota
Department of Chemical Engineering and Materials Science

COST

Total Project Value
$237,393

DOE/Non-DOE Share
$237,393/$0

Primary Project Goal

The primary goal of this project is to develop a new, economic, easily scaled up method for the fabrication of a hydrogen selective silica membrane that has high hydrogen selectivity and flux and is stable at the environmental conditions existing in a water gas shift reactor.

Objectives

The specific objective is to demonstrate the fabrication of a 100 nanometer (nm) or thinner supported film of SiO_2 using a technique that can be easily and economically scaled up and to show that this membrane can meet the following requirements:

- Hydrogen permeance in excess of 10^{-7} mol/m^2-s-Pa with a H_2/CO_2 selectivity in excess of 100 at temperatures in the range of 500-700^{o}C, a pressure of 20 bar, and a stream composition representative of feed to a water gas shift reactor.
- Maintain stable membrane performance at the above values and conditions in the presence of steam (25% H_2O) for at least 1 month.

Benefits

Fossil fuels provide over 80% of the world's energy today and are expected to continue their dominance throughout the foreseeable future. Innovations in technologies that could lead to practical and cost-effective means for either reducing emissions from fossil-fueled power plants or removing CO_2 from the atmosphere could have far-reaching benefits for the economy of the United States. This proposal represents a novel alternative to current technology for the capture and sequestration of CO_2 that could result in a process for the economic production of H_2 from coal supplied synthesis gas while simultaneously producing a concentrated CO_2 stream for sequestration. This approach has the potential to show a significant improvement in performance and cost compared to currently available technologies.

Proj306.pmd

PROJECT facts

Sequestration

03/2005

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

Novel Dual Functional Membrane for Controlling Carbon Dioxide Emissions from Fossil Fueled Power Plants

CONTACTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

José D. Figueroa
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4966
jose.figueroa@netl.doe.gov

C. Jeffrey Brinker
Sandia Fellow, Sandia National Laboratories
Professor of Chemical & Nuclear Engineering,
The University of New Mexico
Advanced Materials Laboratory
1001 University Blvd. SE, Suite 100
Albuquerque, NM 87106
505-272-7627
cjbrink@sandia.gov

Background

There is growing concern among climate scientists that the buildup of greenhouse gases (GHG), particularly carbon dioxide, in the atmosphere is affecting the global climate in ways that could have serious consequences. One approach to reducing GHG emissions is to scrub CO_2 from the flue gas of power plants and sequester it in geologic formations. Although it is technically feasible to remove CO_2 from flue gas, current processes are too expensive. Therefore, new, less expensive processes are needed. This project is investigating the feasibility of developing a novel, dual-functional silica-based membrane for controlling carbon dioxide emissions from fossil-fuel fired power plants.

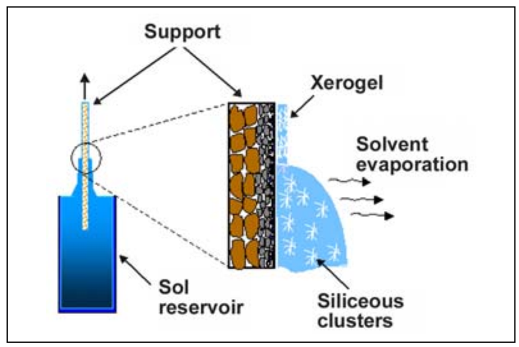


Fig. 1. Schematic representation of the sol-gel dip-coating process for depositing a microporous aminosilicate membrane on a porous tubular ceramic support.

The membrane will be prepared by a sol-gel dip-coating process on a porous support (see Fig. 1) and will consist of a microporous inorganic siliceous matrix with amine functional groups physically immobilized or covalently bonded on the membrane pore walls. It is anticipated that strong interactions between the permeating CO_2 molecules and the amine functional membrane pores will enhance surface diffusion of CO_2 on the pore wall of the membrane with subsequent blocking of the transport of other gases, such as O_2, N_2, and SO_2 (see Fig. 2). In this way, the new membrane is expected to exhibit higher CO_2 selectivity compared to prior, purely siliceous membranes that perform separations based on difference in molecular size only. The pore size of the new membranes will be controlled in the range of 4-10 Å by adjusting the precursor sol composition.

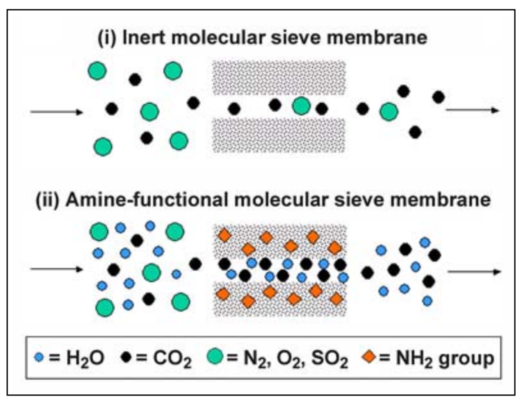


Fig. 2. Gas transport mechanism through: (i) a pure siliceous microporous membrane where separation is mainly based on size differences of permeating molecules, and (ii) a microporous aminosilicate membrane where pore blocking can be achieved by strong interactions of CO_2 and H_2O vapor with the amine groups introduced in the silica matrix.

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

University of New Mexico

T3 Scientific

COST

Total Project Value
$886,827

DOE/Non-DOE Share
$886,827 / $0

Benefits

If CO_2 capture from flue gas is ever to become economically feasible, improved capture processes are needed. The use of an amine modified membrane with high CO_2 permeance and selectivity holds promise for reducing costs by avoiding the expensive absorber/stripper system required with amine based systems.

The amount of solvent (H_2O), the type and amount of surfactant additive, and the sol aging time and their effect on membrane permeability and selectivity will be studied experimentally. The incorporation of the amine functional groups in the silica matrix will be implemented by various techniques: (1) mixing of silica sol with aqueous solution of amines; (2) using aminosilanes as a silicon source for the membrane matrix; and (3) post-grafting terminal amine groups on the pore walls of surfactant-templated membranes, using aminosilanes. The membrane microstructure (see Fig. 3) will be optimized in order to meet a targeted CO_2 permeance as high as $1x10^{-3}$ cm^3(STP)/cm^2.sec.cmHg, combined with a CO_2/N_2 separation factor of over 100.

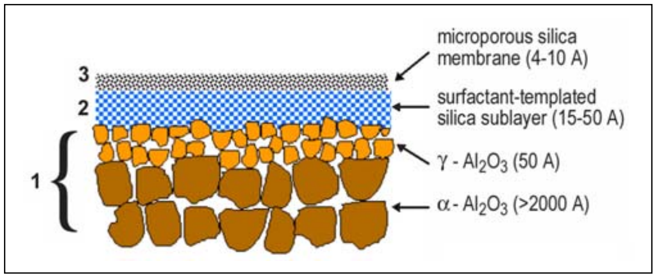


Fig. 3. Overview of the microstructure of the composite membrane comprising of: (1) a commercially available tubular or hollow fiber ceramic support; (2) a mesoporous surfactant-templated silica sub-layer with pore size 15-50 Å; and (3) a microporous aminosilicate gas separation membrane layer with pore size 4-10 Å.

The group at the University of New Mexico will be primarily responsible for laboratory-scale synthesis and testing of the proposed novel membranes, while the team at T3 Scientific will be responsible for commercialization of the technology and design/economic evaluation of an industrial-scale membrane process for CO_2 removal from power plant flue gas.

Primary Project Goal

The primary goal of this project is to develop a dual functional membrane capable of removing CO_2 emissions from the flue gas of coal-fired power plants efficiently and inexpensively.

Objectives

The objectives of this project are to:

- Prepare and characterize amine functional membrane materials with a CO_2/N_2 selectivity of 100 and a CO_2 permeance of $1x10^{-3}$ cm^3(STP)/cm^2·sec·cmHg or greater.
- Conduct small-scale parametric testing, using a simulated multi-component gas, to determine optimum performance conditions.
- Optimize thin membrane deposition.
- Perform a preliminary systems analysis for integration of a membrane system into a 500 MW power plant.
- Perform a long-term test to estimate membrane life.
- Conduct a pilot-scale test.

PROJECT
facts

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

Sequestration

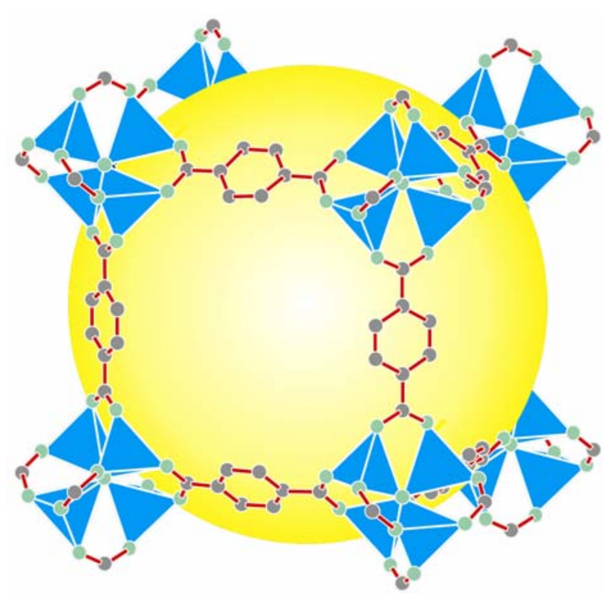
12/2004

CARBON DIOXIDE SEPARATION WITH NOVEL MICROPOROUS METAL ORGANIC FRAMEWORKS

Background

UOP LLC, the University of Michigan, and Northwestern University are collaborating on a three-year program to develop novel microporous metal organic frameworks (MOFs) suitable for CO_2 capture and separation. MOFs are hybrid organic/inorganic structures in which the organic moiety is readily derivatized. This innovative program is using sophisticated molecular modeling to evaluate the structurally diverse, highly porous, thermally stable MOFs, which have shown exceptional storage capacity for methane. Selected MOFs will be optimized for CO_2 selectivity, adsorption capacity, and rates of adsorption and desorption.

This partnership of industry and university researchers brings a novel approach and unique depth of experience to the problem of CO_2 separation and capture. The University of Michigan has extensive experience in the discovery and tailoring of novel MOFs for adsorption of gases, such as methane and hydrogen. In this proposal, the use of MOFs will be extended to CO_2 separation. UOP is a global leader in process chemistry and has developed a broad portfolio of technologies for separating CO_2 from gas streams. Northwestern University will be consulting on molecular modeling.



Molecular structure of the microporous metal organic frameworks (MOFs)

CONTACTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

David A. Lang
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4881
david.lang@netl.doe.gov

Beth McCulloch
External Technology Specialist
UOP LLC
50 East Algonquin Road
Des Plaines, IL 60016
847-391-2653
Beth.McCulloch@uop.com

MOFs are a structurally diverse family of materials with over 500 having been prepared. The proposed technical approach is to use molecular modeling to identify MOFs with the best sorption properties for CO_2 and to predict the structures of new MOFs. Synthesis of the organic linker is an important part of the preparation of novel MOFs. In addition, detailed characterization of the novel materials will be performed to determine the active sorption sites. UOP will perform process modeling and economic analysis of processes designed for the separation and capture of CO_2 from gas mixtures produced by electric utilities.

The core technologies are supported by academic and industrial experience in materials development, materials characterization, and process modeling. Professor Yaghi, from the University of Michigan, brings an in-depth understanding on developing new material topologies with high structural stability, high porosity, and variable pore size and porosity. UOP has a unique capability to understand commercial requirements and to deliver technology and will use these skills to integrate MOF technology into a process for the capture of CO_2 from flue gas and gasifier streams.

Primary Project Goal

The primary goal of this project is to develop a low-cost, novel sorbent to remove CO_2 from flue gas and gasifier streams in coal-fueled power plants. The sorbent will have high selectivity, high adsorption capacity, and good adsorption/desorption rates. In addition, the MOFs will be tailored to minimize the CO_2 binding energy in an effort to reduce the energy required for regeneration.

Objectives

The objectives of the program are:

- To develop a theoretical model to predict the structure of MOFs with good CO_2 sorption properties. This model will allow for the efficient screening of existing MOFs and for the design of new MOFs and the prediction of their sorption properties.
- To develop an understanding of the sorption sites in MOFs.
- To develop MOFs tailored for CO_2 separation from flue gas.
- To develop MOFs tailored for CO_2 separation from gasifier streams.
- To assess the commercial potential of MOFs for separation and capture of CO_2.
- To integrate an MOF-based process into a coal-fueled power plant to recover CO_2 from actual plant-generated gas mixtures.

Benefits

Although oil production in the U.S. has been gradually declining, we have huge reserves of coal. Unfortunately, when coal is burned, it releases more CO_2 per unit of heat than any other fossil fuel, and anthropogenic CO_2 is believed to be contributing to global warming and climate change. Successful completion of this program could lead to a low-cost, novel sorbent to remove CO_2 from flue gas and gasifier streams in electric power plants. The captured CO_2 could then be sequestered to prevent its emission to the atmosphere. This would enable the use of our coal reserves as an energy source without contributing to global warming, while simultaneously creating jobs and reducing our dependence on imported oil.

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

UOP LLC

University of Michigan

Northwestern University

COST

Total Project Value
$900,000

DOE/Non-DOE Share
$900,000/$0

Proj315.pmd

PROJECT facts

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

Sequestration

03/2005

Design and Evaluation of Ionic Liquids as Novel Absorbents

Background

There is growing concern among climate scientists that the buildup of greenhouse gases (GHG), particularly carbon dioxide, in the atmosphere is affecting the global climate in ways that could have serious consequences. One approach to reducing GHG emissions is to scrub CO_2 from the flue gas of power plants and sequester it in geologic formations. Although it is technically feasible to remove CO_2 from flue gas, current processes are too expensive. Therefore, new, less expensive processes are needed. This project is investigating the feasibility of using a novel class of compounds, ionic liquids, for the capture of CO_2 from the flue gas from coal and natural gas fired power plants.

The success of ionic liquids technology will be based on increasing the knowledge base on the chemical characteristics of ionic liquids and on the competitiveness of processes, which utilize ionic liquids based absorbents for CO_2 capture from flue gas streams compared to commercial amine-based technologies. The successful ionic liquid absorbent will have high CO_2 selectivity and capacity (i.e., a Henry's law constant lower than 10 bar) with a low energy requirement for regeneration (i.e., an enthalpy of absorption less than 60 kJ/mol).

Using theoretical calculations and previous experimental data, a diverse set of ionic liquids likely to have desirable CO_2 selectivities and capacities will be identified, synthesized, purified, and characterized. Their basic physical properties will be measured, and they will be simulated at the atomistic level to obtain a fundamental understanding of the factors that control their properties.

Primary Project Goal

The primary goal of this project is to provide a comprehensive evaluation of the feasibility of using a novel class of compounds, ionic liquids, for the capture of CO_2 from the flue gas of coal and natural gas fired power plants.

Objectives

The objectives of the project are to:

- Produce a range of ionic liquid sorbents for further evaluation.
- Determine the fundamental factors influencing the absorption of CO_2 and other gases present in flue gas streams.
- Determine relevant thermo-physical and phase behavior properties.
- Develop a preliminary process design that uses ionic liquids in an absorption separation system.

CONTACTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

José D. Figueroa
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4966
jose.figueroa@netl.doe.gov

Edward J. Maginn
Principal Investigator
Notre Dame
St. Joseph County, IN 46556
574-631-5687
ed@nd.edu

Accomplishments

Eleven ionic liquids have been synthesized or acquired. CO_2 solubility has been measured for five of these compounds, with 1-n-hexyl-3-methylimidazolium tris (pentafluoroethyl) trifluorophosphate showing the best performance to date, having a Henry's constant of 25 bar at 25ºC. By measuring the solubility of other gases in these liquids, including oxygen, ethylene and ethane, it was found that CO_2 is significantly more soluble in these ionic liquids than any of these other gases, Figure 1. Other physical properties, including viscosity and density have been measured for these compounds. The viscosities vary widely at low temperature, but all fall to reasonable values above 40ºC.

First principles quantum mechanics calculations have been conducted to understand the nature of CO_2 absorption in these liquids. The calculations have shown that CO_2 associates primarily with the anion, but that the anion primarily associates with the cation. Thus the CO_2 interacts most strongly with the secondary negatively charged regions of the anion, suggesting that greater negative charge delocalization could lead to enhanced CO_2 solubility. These concepts are being used to identify new targets for synthesis and testing. An example from these calculations is shown in Figure 2.

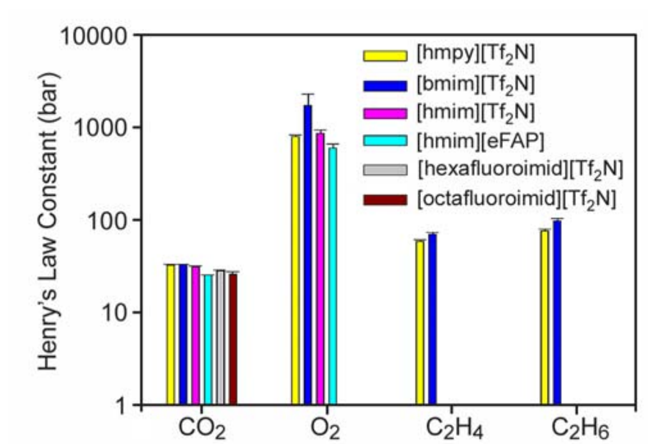
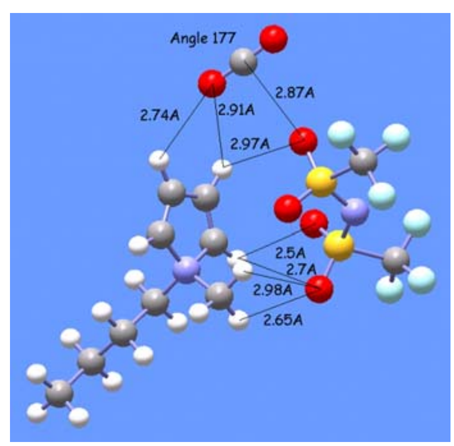


Figure 1: Measured Henry's Law constants for CO_2 in various ionic liquids. A small Henry's Law constant indicates high solubility.

Figure 2: Results of ab initio calculation for CO_2 association with 1-n-butyl-3-methylpyridinium bis (trifluorosulfonyl) amide. Notice that the negative oxygen atoms of the anion are mainly associating with the cation, but can also interact with the positively charged carbon atom on CO_2.



Benefits

If CO_2 capture from flue gas is ever to become economically feasible, improved capture processes are needed. The use of ionic liquids as CO_2 adsorbents holds promise for reducing costs by developing a process with higher CO_2 loading in the circulating liquid and lower heat requirements for regeneration. Both these effects would lower process costs.

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNER

University of Notre Dame

COST

Total Project Value

$404,106

DOE/Non-DOE Share

$404,106 / $0

Project 332.pmd

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

12/2004

NEUTRALIZING CARBONIC ACID IN DEEP CARBONATE STRATA BELOW THE NORTH ATLANTIC

CONTACTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

David Hyman
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-6572
david.hyman@netl.doe.gov

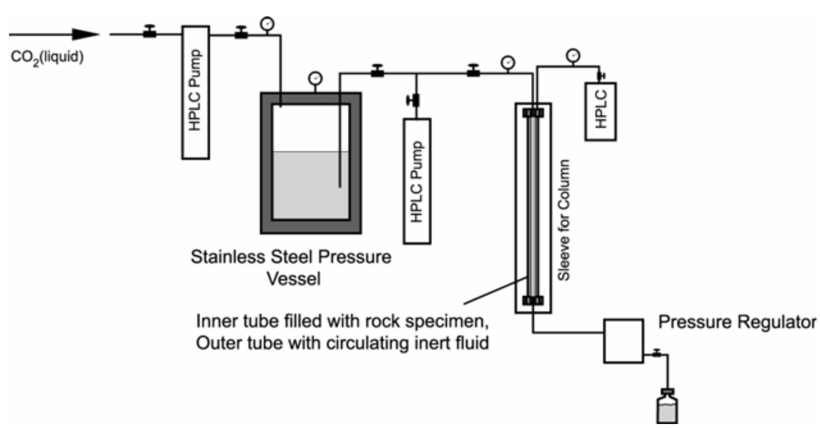
Daniel Schrag
Principal Investigator
Harvard University
20 Oxford Street
Cambridge, MA 02138
617-495-7676
schrag@eps.harvard.edu

Background

The Eastern Seaboard is the most densely populated region in the country and generates a large fraction of all U.S. anthropogenic CO_2 emissions. Disposal options for the large volume of CO_2 produced in this region are limited. Land transport and disposal are difficult due to high population density. From geographical considerations, offshore disposal might seem a reasonable approach. However, a number of technical uncertainties and environmental concerns make it difficult to implement this option. Thus, developing technology that would allow long-term storage of CO_2 in geological reservoirs below the ocean floor would be a major breakthrough for CO_2 sequestration efforts.

The Atlantic ocean is the site of most of the world's deep sea carbonate deposition, with a wide range of sediment compositions ranging from almost pure limestone to marly shales and claystones occurring at a wide range of water depths. A number of potential disposal sites are within 200 miles of the U.S. coastline. Thus, it is essential to the carbon sequestration program to evaluate the suitability of CO_2 storage in deep-sea carbonate sediments as part of an overall strategy of carbon storage and management.

The major advantage of CO_2 injection into carbonate sediments beneath the sea floor is the natural chemical buffer created by the reaction between calcium carbonate and carbonic acid, producing high-alkalinity pore fluid. Unfortunately, the reaction kinetics of CO_2/water mixtures with natural carbonate sediments consisting primarily of microfossils is not well determined at the pressures and temperatures of interest.



Schematic drawing of the experimental system

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

Harvard University

Columbia University

Carnegie-Mellon University

U.C. Santa Cruz

COST

Total Project Value
$801,374

DOE/Non-DOE Share
$801,374/$0

The technical issues of injection are relatively straightforward, although some questions do exist. Drilling into carbonate sediments is relatively easy. At shallow depth below the ocean floor these deposits have high porosity but very little structural integrity. At deeper levels, they have lower porosity and would allow little flow. However, oil extraction from such fields shows that hydrofracturing is a viable option. Also, after a relatively short period of injection, dissolution of carbonate material could provide greatly increased permeability. The calcium carbonate present will be consumed in neutralizing carbonic acid and leave behind an increased pore volume filled with calcium bicarbonate solution.

Thus, disposal by injection into carbonate sediments below the sea floor could provide an extremely large sink for CO_2; the CO_2 would be neutralized in a chemical reaction that turns solid calcium carbonate into dissolved bicarbonate. The physical characteristics of the reservoir would provide a series of barriers to the escape of the CO_2. If the bicarbonate-rich pore fluid did mix with seawater, then the ocean would provide an additional safeguard. Effects on the atmosphere, even on the time scale of millennia, would be extremely small, and the process should qualify as a near-permanent sequestration method.

Primary Project Goal

The primary goal is to investigate the feasibility of carbon dioxide disposal by injection and neutralization below the ocean floor in calcium carbonate sediments.

Objectives

- To understand the mechanical and chemical behavior of CO_2 and CO_2/water mixtures injected into carbonate sediments of various compositions under a range of pressures and temperatures.
- To investigate the kinetics of calcium carbonate dissolution in the presence of CO_2/water.
- To investigate the possibility of CO_2 hydrate formation in the pore fluid.
- To conduct an economic analysis to estimate costs of drilling, gas injection, and site monitoring.

Accomplishments

New project.

Benefits

There is growing concern that anthropogenic CO_2 emissions are contributing to global climate change. To mitigate this problem, it may become necessary to sequester CO_2. However, although the East Coast of the U.S. generates a large volume of CO_2, sequestration sites are somewhat limited. An obvious sink is the Atlantic Ocean, but technical and environmental concerns for most ocean sequestration options make their implementation difficult. An option that appears to avoid most concerns is to inject CO_2 into ocean carbonate sediments. The CO_2 would react to form bicarbonate ions which should be permanently trapped. Even if they should slowly migrate to ocean waters, their impact on the ocean should be minimal. Thus, this project is exploring an option that could be very beneficial in meeting our goal of reducing CO_2 intensity by 18% by 2012.

PROJECT facts

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

Sequestration

08/2004

A Novel Approach to Mineral Carbonation: Enhancing Carbonation While Avoiding Mineral Pretreatment Process Cost

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

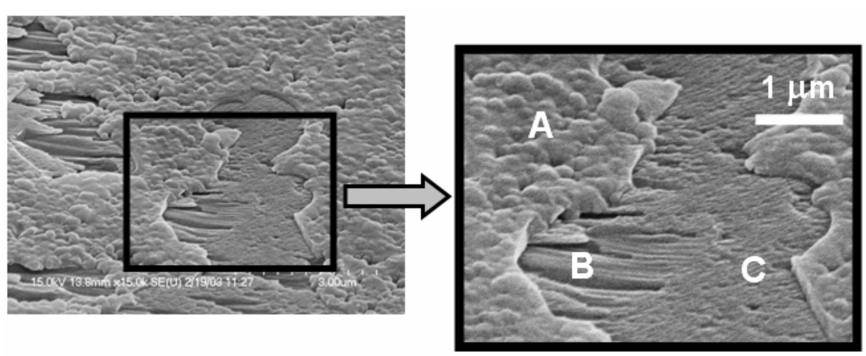
David A. Lang
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4881
david.lang@netl.doe.gov

Michael J. McKelvy
Arizona State University
Center for Solid State Science
Tempe, AZ 85287-1704
480-965-4535
mckelvy@asu.edu

Background

If the environmental problems associated with CO_2 emissions can be overcome, known fossil fuel reserves, especially coal, can support global energy demands for many years. One option is to sequester CO_2 emissions. However, many CO_2 sequestration candidate technologies that propose long-term storage need to be carefully monitored to ensure that the sequestered CO_2 does not leak into the atmosphere. Unlike these processes, mineral sequestration provides permanent disposal by forming geologically stable mineral carbonates. Carbonation of the widely occurring minerals of the olivine group, such as forsterite (Mg_2SiO_4), is a potential large-scale sequestration process that converts CO_2 into the environmentally benign mineral magnesite ($MgCO_3$). Because the process is exothermic, it inherently offers low cost potential. Enhancing carbonation reactivity is the key to economic viability.

Recent studies at the U.S. DOE Albany Research Center (ARC) have established that aqueous-solution carbonation using supercritical CO_2 is a promising process; even without olivine activation, 30-50% carbonation has been achieved in an hour. Mechanical activation by attrition accelerated the carbonation process to an industrial timescale (near completion in less than an hour) at reduced pressure and temperature. However, the activation cost is too high to be economical and lower cost pretreatment options are needed. The Arizona State University Center for Solid State Science proposes a novel approach that offers the potential to dramatically enhance carbonation reactivity while bypassing any pretreatment/activation.



Scanning electron micrograph showing silica-rich passivating layer exfoliation. A) the passivating layer; B) a recently fractured and exfoliated region exposing part of the olivine particle core; C) a new passivating layer beginning to grow in the exfoliated region.

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PROJECT TEAM

Michael J. McKelvy
Andrew V.G. Chizmeshya
Kyle Squires
Ray W. Carpenter

PARTNER

Arizona State University

COST

Total Project Value
$558,663

DOE/Non-DOE Share
$430,482/$128,181

Recent mechanistic investigations have shown that robust silica-rich layers form on an olivine surface during carbonation. As carbonation proceeds, these passivating layers thicken, fracture, and eventually exfoliate, exposing fresh olivine surfaces. Particle-particle and particle-wall collisions within the slurry stream can dramatically impact both the exfoliation rate and the extent of carbonation. Order of magnitude increases in the extent of carbonation have been observed for different flow systems. In order to identify key parameters that can enhance carbonation, it is proposed to explore exfoliation mechanisms and their relationship to enhanced carbonation using three innovative approaches:

- Multiphase fluid modeling and experimental investigations to elucidate key fluid-flow parameters that facilitate the slurry interactions that enhance exfoliation.
- Chemical studies to establish the potential for controlling passivating layer effectiveness and exfoliation rate by adjusting aqueous cation size (e.g., Li^+, Na^+, K^+).
- Sonic investigations to elucidate the potential that controlled sonication offers to enhance exfoliation and particle cracking.

Once the key parameters for each approach are identified, they will be integrated to evaluate their combined potential to synergistically enhance exfoliation and carbonation. The above studies will be complemented by detailed morphological, structural, and compositional investigations of their intermediate and final reaction products down to the nanoscale. These studies will be further integrated with advanced computational modeling of key phenomena to develop an atomic-level understanding of the mechanisms that govern carbonation reactivity and exfoliation.

Primary Project Goal

The primary goal is to develop the understanding needed to engineer a new low-cost mineral carbonation process that avoids the cost of pretreatment/activation.

Objectives

The objectives of this project are to:

- Explore novel low-cost approaches with the potential to facilitate olivine passivating layer exfoliation to enhance olivine carbonation.
- Investigate the impact these approaches have on exfoliation and carbonation mechanisms.

Benefits

Mineral sequestration processes have the potential to permanently dispose of CO_2 in geologically stable mineral carbonate rocks that will not require continuous monitoring, which is required with many other CO_2 sequestration technologies. The technology to be developed under this proposal will hasten the natural mechanism of turning CO_2 into a solid. The solidification process could be accomplished in less than an hour rather than in hundreds of thousands of years via natural mineral weathering. Having an effective, economic method for permanently sequestering CO_2 would allow continued use of our abundant coal reserves.

PROJECT facts

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

Sequestration

01/2005

A NOVEL APPROACH TO EXPERIMENTAL STUDIES OF MINERAL DISSOLUTION KINETICS

CONTACTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

David A. Lang
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4881
david.lang@netl.doe.gov

Chen Zhu
Indiana University
Department of Geological Sciences
1001 East 10th Street
Bloomington, IN 47405
812-856-1884
chenzhu@indiana.edu

Background

DOE is conducting pilot CO_2 injection tests to evaluate the concept of geologic sequestration. One strategy that has the potential to enhance CO_2 solubility and reduce the risk of CO_2 leaking back to the surface is dissolution of indigenous minerals in the geological formation and formation of secondary carbonate precipitates. This both increases the brine pH and immobilizes the CO_2. Clearly, the rates at which these dissolution and precipitation reactions occur directly determine the efficiency of this option. However, one of the fundamental problems in modern geochemistry is the persistent two to five orders of magnitude discrepancy between laboratory-measured and field-derived feldspar dissolution rates.

To date, there is no real guidance on how to predict silicate reaction rates for use in quantitative models. Current models for assessment of geological carbon sequestration have generally opted to use laboratory rates, in spite of the dearth of such data for compositionally complex systems and the persistent disconnect between laboratory and field applications. Therefore, a firm scientific basis for predicting silicate reaction kinetics in geological formations containing injected CO_2 is urgently needed to ensure the reliability of the geochemical models used for the assessment of carbon sequestration strategies.

Feldspar is the most abundant mineral in the Earth's crust.

The proposed experimental and theoretical study attempts to resolve this outstanding scientific issue by a novel experimental design and theoretical interpretation to measure silicate and dawsonite dissolution rates and iron carbonate precipitation rates at conditions pertinent to geological carbon sequestration. Additionally, this project will experimentally test the novel idea of storing CO_2 together with SO_2 contaminants in redbed sandstones that contain both feldspars and iron oxides. It is expected that SO_2 will reduce ferric iron to ferrous iron, which reacts with CO_2 and precipitates iron carbonate. If the SO_2 impurity in flue gas has a beneficial use in geological carbon sequestration, this represents a major cost reduction in front-end processing. The proposed experimental design and data interpretation depart significantly from the state-of-the-art practice, and the results will provide a guide to the evaluation of geological sequestration. Furthermore, an atomic scale, or near atomic scale, electron microscopic study will reveal reaction mechanisms that will also benefit the ongoing mineral carbonation and brine carbonation programs.

Primary Project Goal

The primary goal of this project is to resolve a long-term controversy that laboratory measured silicate dissolution rates are consistently two to five orders of magnitude faster than field-derived rates. This controversy is one of the major obstacles to quantitatively evaluating the efficacy of geological carbon sequestration.

Objectives

- To develop an experimental design and an interpretation of results to determine the rate of feldspar dissolution in geologic formations.
- To experimentally test the novel idea of storing CO_2 together with SO_2 contaminants in redbed sandstones that contain both feldspars and iron oxides.

Benefits

The results of this work will provide guidance with respect to the rates and rate laws that should be used in performance assessments and will also benefit the mineral carbonation and brine carbonation programs. This may lead to improvements in the geologic sequestration of CO_2. Any reduction in the cost of CO_2 sequestration would have a positive effect on the economy should if become necessary to reduce the emissions of CO_2 to the atmosphere.

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

Indiana University

University of Minnesota

COST

Total Project Value
$426,701

DOE/Non-DOE Share
$426,701/$0

PROJECT facts

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

Sequestration

09/2004

NETL

CONTACTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Dawn Chapman
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-4133
dawn.chapman@netl.doe.gov

Mark A. Eiteman
Professor of Engineering
408 Driftmier Engineering
University of Georgia
Athens, GA 30602
706-542-0833
eiteman@engr.uga.edu

Process Design for the Biocatalysis of Value-Added Chemicals from CO_2

Background

Organic compounds available from U.S. agricultural enterprises include glycerol, a renewable material generated as a by-product in the production of biodiesel, whose production volume is anticipated to increase significantly, and glucose, the primary carbohydrate generated from agricultural enterprises in the U.S., such as corn wet-milling. This project is studying the production of a suite of specialty chemicals by biocatalytic fixation of CO_2 and co-substrates, such as glycerol and glucose. Although several chemical products can be produced using the sequestration technology being developed by this project, the focus of this study is on succinic acid. Recent advances in the metabolic engineering of the production microbes have made feasible the commercial biosynthesis of succinic acid from CO_2 and these co-substrates.

The biochemical pathways leading to succinic acid are similar in structure to those of *acrhaea*. However, unlike many species of *archaea*, the bacterium used in this project can attain a high cell density in a short time and, thereby, provide high productivities, does not have fastidious media requirements, is well characterized genetically, does not require light to generate ATP, and is immediately amenable to process scale-up. Moreover, the proposed biocatalytic process is designed to operate under non-growth (stationary phase) conditions. This permits a high product yield to be achieved and minimizes the formation of excess biomass.

Sample being withdrawing from 14 liter pilot scale fermentor

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNER

University of Georgia Research Foundation, Inc.

COST

Total Project Value
$384,275

DOE/Non-DOE Share
$384,275/$0

Primary Project Goal

The primary goal of this project is to produce a suite of specialty chemicals by biocatalytic fixation of CO_2 with other inexpensive organic substrates, such as glycerol and glucose. The primary product from this operation is succinic acid.

Objectives

The objectives of this project are to:

- Modify the bacterial strain to make it suitable for industrial applications.
- Evaluate process robustness.
- Evaluate succinic acid production as a function of CO_2 mass transfer.
- Determine the effect of other process variables, such as pH and H_2 in the gas stream.
- Determine the effect of NO_X and SO_X and other potential inhibitors in flue gas.
- Optimize the fermentation medium to achieve and maintain a high cell density which supports succinic acid production.
- Develop a reactor design that optimizes CO_2 mass transfer and produces succinic acid at high rates and yields.

Benefits

This biological reaction to sequester CO_2 promises to be a practical way to convert CO_2 into value-added chemicals. An advantage of this process is the potential to use flue gas directly in the succinic acid production process and, thus, avoid the need for CO_2 capture and transport. The anticipated future application of the project will result in the synthesis of other chemical products from CO_2, such as formic acid, malic acid, and fumaric acid. This research will form the basis of a biorefinery approach for the production of value-added chemicals from CO_2 and serve as a niche process for CO_2 sequestration.

Packed trickle bed reactor setup

Proj310.pmd

Non-CO_2 GHG Mitigation

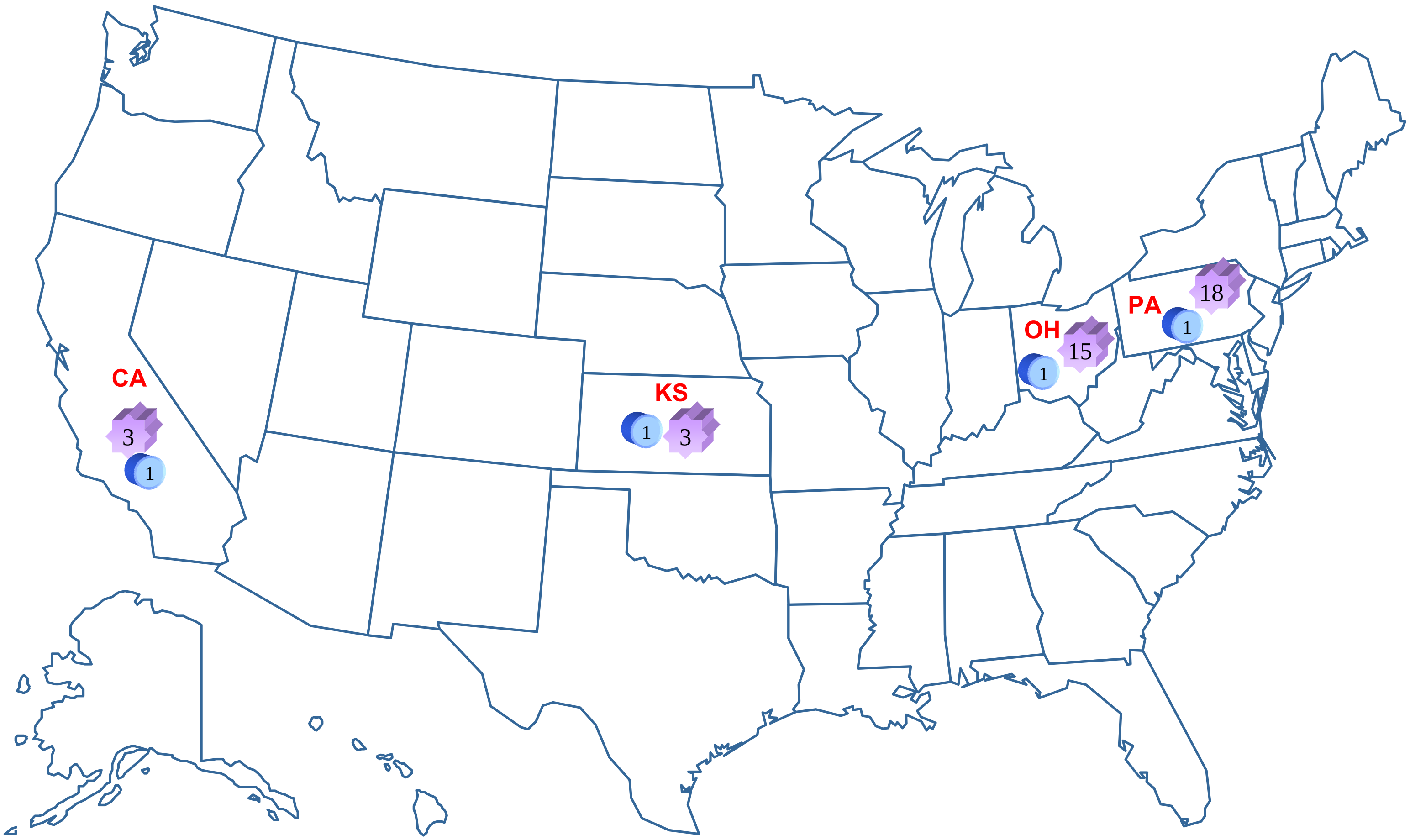
Page left blank to accommodate 2-sided printing

Non CO_2 GHG Mitigation Projects

LEGEND

Number of Non CO_2 GHG Projects

Congressional District



*Doesn't include NETL Projects

Project Title	Primary Contractor	Congressional District
Full-Scale Bioreactor Landfill	Yolo County	CA03
Capture and Use of Coal Mine Ventilation Air Methane	CONSOL Energy Inc.	PA18
Upgrading Methane Streams with Ultra-Fast TSA	Velocys, Inc.	OH15
Landfill Gas Sequestration in Kansas	Kansas Geological Survey	KS03

Non-CO_2 GHG Mitigation

Technology Target

- Demonstration viability of large-scale oxidation of coal mine ventilation air methane
- Technology options for land fill gas
- Upgrade low Btu methane streams from coal mines and landfill gas

Yolo
- Full-scale Bioreactor Landfill for abating GHG related to organic wastes
- Data collection & monitoring of landfill methane gas with bioreactors

CONSOL
- Use of coal mine ventilation air methane
- Demonstration flow reversal of ventilation air methane

VELOCYS
- Separation of nitrogen from methane

Kansas Geological Survey
- Landfill gas sequestration and natural processing in coal seams

* Factsheet Under Development

FULL-SCALE BIOREACTOR LANDFILL

Background

Sanitary landfilling is the dominant method of solid waste disposal in the United States, accounting for about 217 million tons of waste annually (U.S. EPA, 1997). The annual production of municipal waste in the United States has more than doubled since 1960. In spite of increasing rates of reuse and recycling, population and economic growth will continue to render landfilling as an important and necessary component of solid waste management.

As a part of the Environmental Protection Agency's (EPA) Project XL program to develop innovative approaches while providing superior greenhouse gas emissions protection, the Yolo County Department of Planning and Public Works is constructing a full-scale bioreactor landfill. In a bioreactor landfill, controlled quantities of liquid (leachate, groundwater, grey-water, etc.) are added to increase the moisture content of the waste. Leachate is then recirculated as necessary to maintain the moisture of the waste at or near its moisture holding capacity. This process significantly increases the biodegradation rate of waste and thus decreases the waste stabilization and composting time (5 to 10 years) relative to what would occur within a conventional landfill (30 to 50 years or more). If the waste decomposes in the absence of oxygen (anaerobically), it produces landfill gas, primarily a mixture of methane, a greenhouse gas. Methane is 21 times more potent than CO_2 in its effects on the atmosphere. This by-product of anaerobic landfill waste composting can be a substantial renewable energy resource that can be recovered for electricity or other uses.

In the initial phase of this project, a 12-acre module divided into several cells was constructed. The cells are highly instrumented to monitor bioreactor performance. The final phase pertaining to carbon sequestration involves evaluating full-scale performance and potential of aerobic and anaerobic bioreactor landfill cells as tools for abating greenhouse gas (GHG) emissions related to organic wastes in landfills.

Primary Project Goal

The goals of this project are to construct, then evaluate full-scale performance and potential of aerobic and anaerobic bioreactor landfill cells as tools for abating greenhouse gas emissions related to organic wastes in landfills. The greenhouse gas (GHG) abatement is accomplished by routes including sequestration of photosynthetically derived carbon in wastes, CO_2 offsets from energy use of waste-derived gas, and mitigation of methane emission from the wastes.

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Karen Cohen
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-6667
karen.cohen@netl.doe.gov

Ramin Yazdani
Senior Civil Engineer
Yolo County Planning and Public Works Department
292 West Beamer Street
Woodland, CA 95695
530-666-8848
ramin.yazdani@ccm.yolocounty.org

PRIMARY PARTNER

Yolo County

Solid Waste Association of North America

Institute for Environmental Management

University of Delaware

COST

Total Project Value:	$1,837,351
DOE:	$ 592,000
Non-DOE Share:	$1,245,351

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

Objectives

- Evaluate full-scale performance and potential of aerobic and anaerobic bioreactor landfill cells as tools for abating GHG emissions related to organic wastes in landfills.
- Operate and measure the performance of anaerobic an bioreactor module to desired endpoint
- Conduct analysis and interpretation of the data.

Accomplishments

In the initial phase of this project, the landfill cells have been constructed and filled with waste. Instrumentation, monitoring, and gas collection systems are in place and used to measure and independently record data from each other. The data from these sensors is automatically recorded and sent to the Yolo County office. Partitioning tracer tests using injection and extraction wells are planned to aid in assessing landfill characteristics including moisture content.

Benefits

This process will significantly increase the biodegradation rate of waste and thus reduce the waste stabilization and composting time by 67-80% and provide a substantially improved renewable energy resource that can be recovered for electricity or other uses. This means that the energy market could increasingly depend on this type of renewable energy for the provision of electric generation. Another benefit of the bioreactor landfill is that it generally improves the gas generation rate, decreasing the time frame of landfill gas generation from several decades to between 5 to 10 years.

A covered bioreactor landfill

Filling a bioreactor landfill

Proj199.pmd

PROJECT facts

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

Sequestration

02/2004

CAPTURE AND USE OF COAL MINE VENTILATION AIR METHANE

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

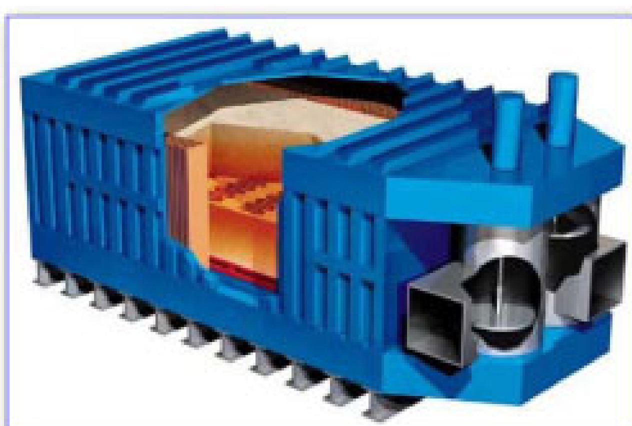
David Hyman
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-6572
david.hyman@netl.doe.gov

Frank Burke
Project Manager
CONSOL Energy
4000 Brownsville Road
South Park, PA 15129
412-854-6676
frankburke@consolenergy.com

Background

Methane emissions from coal mines represent about 10% of the U.S. anthropogenic methane released to the atmosphere. Methane, the second most important non-water greenhouse gas, is 21 times as powerful as CO_2 in its postulated global warming effect. Ventilation air methane (VAM), that is, methane in the exhaust air from underground coal mines, is the largest source of coal mine methane, accounting for about 60% of the methane emitted from coal mines in the U.S. Unfortunately, because of the low concentration of methane (0.3-1.5%) in ventilation air, it is difficult to use the methane beneficially. However, oxidizing methane to CO_2 and water reduces its global warming potential by 87%. A potential way to oxidize the methane is by use of a thermal flow reversal reactor (TFRR).

The TFRR technology employs the principle of regenerative heat exchange between a gas and a solid bed of a heat exchange medium. VAM flows into and through the reactor in one direction, and the temperature is increased until the methane is oxidized. The hot products of oxidation then lose heat as they continue toward the far side of the bed. At a specified interval, the flow is automatically reversed, so that the part of the bed that was previously heated now heats the incoming gas. Through the use of heat exchange, excess heat may be transferred for local heating needs or for the production of electric power.



Internal View of TFRR - Visible are heating coil, insulation, switching valves, and air plenum

MEGTEC manufactures such a reactor, which they call VOCSIDIZER. The VOCSIDIZER system consists of a large bed of ceramic material in an airtight steel container. A process fan forces the ventilation air into the plenum chamber either above or below the bed. Valves typically reverse flow every two minutes. Electrical heating elements heat the center of the bed to 1,832°F at startup, and the reversal of the flow through the bed keeps the center hot during operation.

Contingent upon MSHA approval, CONSOL Energy will demonstrate a commercial-scale (60,000 cfm of ventilation air) VOCSIDIZER oxidation system sited at an operating coal mine for a one-year period. The project includes site selection and permitting, detailed design of the oxidation system, procurement, start up, and commissioning of the system. This will be followed by 12 months of operation. The performance data generated will allow the feasibility and economics of energy recovery from the system to be determined. An engineering and economic analysis of a 180,000 cfm system (sized to consume the majority of VAM from a large mine), including energy recovery, will be conducted.

Potential test site at CONSOL's mine ventilation fan in Southwest Pennsylvania

Primary Project Goal

The primary goal is to determine the long-term technical and economic feasibility of applying a full-scale TFRR system to the safe and efficient oxidation of VAM from operation of a large underground coal mine.

Objectives

- Design an effective interface between the TFRR and the mine ventilation system that does not compromise mine safety
- Convert the low and variable concentration of methane in the coal mine ventilation air to carbon dioxide effectively and efficiently
- Determine the cost of applying the technology
- Determine the quantity of useful energy that can be economically produced

Accomplishments

- Basic designs have been prepared
- Negotiations are underway with MSHA to permit the TFRR unit at an active coal mine

Benefits

The CONSOL team proposes to demonstrate the capture and use of coal mine VAM through use of a full-scale TFRR system. This technology holds the potential to significantly reduce the global warming tendency of the methane emitted from underground coal mines while simultaneously permitting the recovery of useful energy. Once demonstrated, this technology could be applied on a large scale and make a major contribution to reducing greenhouse gas emissions.

Proj248.pmd

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

CONSOL Energy

COST

Total Project Value:
$2,029,646

DOE/Non-DOE Share:
$1,623,716 / $405,930

PROJECT facts

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

Sequestration

02/2004

Upgrading Methane Streams with Ultra-Fast TSA

Background

Most natural gas streams are contaminated with other materials, such as hydrogen sulfide (H_2S), carbon dioxide (CO_2), and nitrogen. Effective processes for removal of H_2S and CO_2 exist, but because of its relative inertness, nitrogen removal is more difficult and expensive. This project will focus on the separation of nitrogen from methane, which is one of the most significant challenges in recovering low-purity methane streams. The approach is based on applying Velocys' modular microchannel process technology (MPT) to achieve ultra-fast thermal swing adsorption (TSA). MPT employs small process channels to greatly enhance heat and mass transfer. Enhanced heat transfer allows TSA cycle times of seconds compared to hours for conventional TSA systems and enables compact, economic systems for upgrading methane streams to pipeline quality.

Primary Project Goal

The primary goal of this project is to design and demonstrate a revolutionary approach to upgrading low-Btu methane streams from coal mines, landfills, and other sub-quality sources, based on applying Velocys' modular MPT to achieve ultra-fast TSA.

Objectives

This project is a two-phased effort. The objective of Phase I is to assess the technical and market feasibility of an microchannel process technology - based thermal swing adsorption (MPT-based TSA) approach for upgrading low-BTU methane streams. The three key tasks during Phase I are:

1. selecting an absorbent for use in a microchannel-based TSA unit
2. designing the MPT-based system and components
3. completing a process feasibility assessment

The objective of Phase II is to conduct bench-scale demonstration of Ultra-Fast TSA.

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Dawn Chapman
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-4133
Dawn.Chapman@netl.doe.gov

Anna Lee Tonkovich
Velocys, Inc.
7950 Corporate Blvd.
Plain City, OH 43064
614-733-3330
tonkovich@velocys.com

BUSINESS CONTACT

Lisa A Johnson
916-654-4276
916-654-4076 fax
ljohnson@energy.state.ca.us

TECHNICAL CONTACT

Terry Surles
916-654-4878
916-654-4676 fax
tsurles@energy.state.ca.us

BUSINESS OFFICE ADDRESS

1516 9th Street, MS 1
Sacramento, CA 95814-5512

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

Velocys, Inc.
D'Amico Technologies

COST

Total Project Value:
$498,928

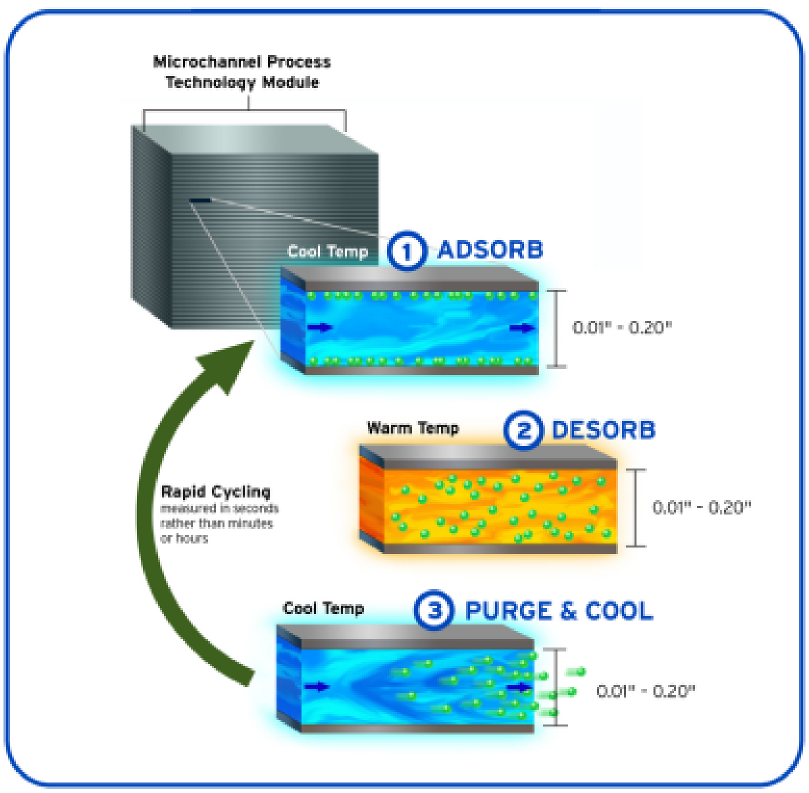
DOE/Non-DOE Share:
$398,928 / $100,000

Accomplishments

A one tier assessment of adsorbents, based on a literature search, has been completed and indicates that activated carbon looks promising. Preliminary tests have been initiated and include collecting methane and nitrogen capacity over several temperatures, compositions, and pressures. Planning for a conceptual system design has been initiated to guide the experimental test matrix.

Benefits

Successful completion of this project would enable recovery of methane from low-grade, previously uneconomic sources, such as coal mine ventilation gas and land fill gas. Because methane is a more powerful greenhouse gas than carbon dioxide, preventing methane emissions to the atmosphere is very important. Commercial deployment of this technology has the potential to reduce annual U.S. greenhouse gas emissions by 23.5 million tonnes of carbon dioxide equivalent while simultaneously recovering 3.5 trillion standard cubic feet of natural gas.



Conceptual scheme of the Ultra-Fast TSA process.

Proj253.pmd

PROJECT facts

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

Sequestration

02/2005

LANDFILL GAS SEQUESTRATION IN KANSAS

CONTACTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Charles Byrer
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-4547
charles.byrer@netl.doe.gov

David Newell
Project Manager
Kansas Geological Survey
1930 Constant Avenue
Lawrence, KS 66045
785-864-2183
dnewell@kgs.uk.edu

Background

Most methane (CH_4) generated by anaerobic decomposition of the organic material in solid-waste-disposal landfills is either vented to the atmosphere or converted to carbon dioxide (CO_2) by flaring. In 2001, U.S. anthropogenic methane emissions totaled 28.0 Mt (1.3 trillion cubic feet - Tcf). Landfills are the single largest source of these emissions, totaling 8.14 Mt (0.38 Tcf) or 29%. Overall, methane emissions account for about 9.3% of the total U.S. greenhouse-gas emissions when weighted by methane's global warming potential factor. Gas-to-energy projects, including upgrading landfill gas (LFG) to pipeline natural gas, are eligible for an "unconventional gas" tax credit. However, this tax credit provides insufficient incentive for development of new LFG-to-energy projects. Unless methane recovery from landfills increases, the increasing tonnage of a landfill waste will result in high levels of methane emissions from this source in the future.

The Kansas Geological Survey will address the gas-processing cost issue by investigating the possibility of injecting LFG into subsurface coalbeds, thus utilizing natural processes to produce larger quantities of higher quality gas by stripping and sequestering CO_2 and non-methane volatile organic compounds out of the LFG onto the surface of a coal seam. About 4.5 million cubic feet of landfill gas is collected through wells in the Johnson County Kansas landfill each day. About half of the landfill gas is methane and the other half is largely carbon dioxide. The methane is separated out of the LFG, cleaned and injected into a pipeline for distribution.

Landfill gas from the Johnson County Landfill is pumped to a gas treatment and processing facility to separate the methane from carbon dioxide and other non-methane compounds. Currently, approximately 5million cfd of landfill gas is treated daily which results in about 3 million cfd of pipeline quality natural gas. The outcome of this project could eliminate such processing facilities by using nature coalbeds to perform the methane separation and sequester the CO_2 component of LFG. (reference: Johnson County, Kansas Environmental Department)

The geology of the Johnson County landfill will be evaluated to determine structure, stratigraphy, and depth and thickness of underlying coal seams. Coals will be obtained and their properties and reservoir conditions ascertained. The physical response of the coal to LFG gas at reservoir conditions will be performed. From these data, reservoir simulations will explore the economic potential for the dual benefit of carbon sequestration and enhanced coalbed methane (ECBM) recovery. A listing of major U.S. landfills overlying coal-bearing strata will be developed, and the feasibility for this type of linked energy system will be rated.

Primary Project Goal

The primary project goal is to experimentally study the reservoir mechanisms and feasibility of subsurface processing of LFG using coal seams and, in exchange, sequester the CO_2.

Objectives

Project objectives are:

- The collection and laboratory testing of coal-bearing cores from underneath a major urban landfill.
- Testing of coal bearing cores from underneath a major urban landfill.
- Experimentally studying reservoir mechanisms.
- Evaluating the feasibility of subsurface processing of LFG using the coal seams that are located under the Johnson County Landfill in eastern Kansas.

Benefits

The project will decrease fugitive greenhouse gas emissions (both methane and CO_2) by sequestering CO_2 and providing methane for home heating, industry, and uses. Working with the EPA will help DOE to assess the role that non-CO_2 greenhouse gas emissions abatement can play in a nationwide strategy for reducing greenhouse gas intensity.

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

Kansas Geological Survey

Kansas University Energy Research Center

Deffenbaugh Industries

Kansas City LFG, LLC

Oak Ridge National Laboratory

COST

Total Project Value
$130,899

DOE/Non-DOE Share
$86,408 / $44,491

Small Business Innovation Research Program

(SBIR)

Page left blank to accommodate 2-sided printing

Small Business Innovation Research Program (SBIR)

DOE provides assistance to Small Business centered research and development through the Small Business Innovative Research Program (SBIR) and the related Small Business Technology Transfer Programs (STTR). The SBIR program was created by the Small Business Innovative Development Act of 1982 and re-authorized by the Small Business Research and Development Enhancement Act of 1992, which also created the STTR program.

The STTR was re-authorized by the Small Business Reauthorization Act of 1997. These two programs are similar except the STTR program requires the collaboration of a non-profit research institution such a s college or university. Both the SBIR and STTR used a phased award process. Only research conducted in the United States is eligible for application and the principal investigator must be a full time employee of the Small Business. In addition, Phase II applications are limited to projects that were Phase I awardees in the 12 months previous to the Phase II solicitation.

Additional information on the SBIR and STTR Programs is available at either the Small Business Administration SBIR/STTR website, by calling the SBIR/STTR Hot Line (301) 903-5707, or by E-mail at SBIR-STTR@science.doe.gov

Project Title	Primary Contractor	Fact Sheet Listing
Integrating MEA Regeneration with CO_2 Compression and Peaking to Reduce CO_2 Capture Costs	Trimeric Corporation	SB-3
Carbon Dioxide Capture from Large Point Sources	Compact Membrane Systems, Inc.	SB-5
Carbon Dioxide Recovery from Combustion Flue Gas Using Carbon-Supported Amine Sorbents	Advanced Fuel Research, Inc.	SB-7
Multiple-Input Data Acquisition Systems (MIDAS) for Measuring the Carbon Content in Soil Using Inelastic Neutron Scattering	X-Ray Associates	SB-9
Instrumentation Systems for Monitoring and Verifying Carbon Sequestration in Terrestrial Systems	Zimmerman Associates	SB-11

* Factsheet Under Development

PROJECT **facts**

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

Sequestration

08/2004

Integrating Mono Ethanol Amine (MEA) Regeneration with CO_2 Compression and Peaking to Reduce CO_2 Capture Costs

CONTACT POINTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

José D. Figueroa
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4966
jose.figueroa@netl.doe.gov

Kevin S. Fisher
Principal Engineer
Trimeric Corporation
107 S. Austin Street
Buda, TX 78610
512-431-6323
kevin.fisher@trimeric.com

Background

In Phase I, Trimeric Corporation, in collaboration with the University of Texas at Austin, will perform the engineering and economic analyses necessary to determine the feasibility of novel MEA processing schemes aimed at reducing the cost of CO_2 capture from flue gas. These novel MEA-based CO_2 capture schemes will be integrated into a coal-fired power plant with the aim of reducing costs and improving efficiency.

Primary Project Goal

The primary goal of this project is to reduce the cost of MEA scrubbing for the recovery of CO_2 from flue gas by improved process integration.

Objectives

The objective is to evaluate various schemes for integrating MEA regeneration into the overall system to improve MEA economics and decrease the cost of CO_2 capture from the flue gas from coal-fired power plants.

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

Trimeric Corporation

University of Texas at Austin

COST

Total Project Value
$99,969

DOE/Non-DOE Share
$99,969/$0

Benefits

MEA-based processes are well established in industry for the recovery of acid gases from process streams. A major factor preventing their use for recovering CO_2 from stack gases is cost. This project could reduce the cost of MEA scrubbing, thus increasing the prospect of being able to capture and sequester CO_2 without a detrimental impact on our economy.

PROJECT facts

Sequestration

09/2004

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

CARBON DIOXIDE CAPTURE FROM LARGE POINT SOURCES

Background

Capture of carbon dioxide at the source of its emission has been a major focus in greenhouse gas emission control. Current technologies used for capturing CO_2 suffer from inefficient mass transfer and economics.

In phase I, Compact Membrane Systems, Inc. will fabricate and test a membrane-based absorption system for the removal of carbon dioxide from a simulated power-plant flue gas. The stability of the membrane system under various operating conditions and chemical environments will be tested.

Primary Project Goal

The primary goal of this project is to develop a membrane-based absorption system that reduces the cost of CO_2 capture from large point sources, such as power plant stacks.

CONTACTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

David A. Lang
Project Manager
National Energy Technology Laboratoryl
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4881
david.lang@netl.doe.gov

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PRINCIPAL INVESTIGATOR

John Bowser
Compact Membrane Systems, Inc.
325 Water Street
Wilmington, DE 19804
302-999-7996
john.bowser@compactmembrane.com

PARTNER

Compact Membrane Systems, Inc.

COST

Total Project Value
$100,000

DOE/Non-DOE Share
$100,000/$0

Objectives

The objective is to improve the economics of CO_2 capture from large point sources by developing a membrane-based absorption system that is an improvement over existing technology

Benefits

The United States has set a goal of reducing the CO_2 emissions intensity of economic activity (pounds of CO_2 emitted per dollar of GDP) by 18% by 2012. In order to meet this goal, we must improve existing technology for capture of CO_2 from flue gas. Existing processes are technically feasible, but economically unsatisfactory. This project has the potential to move us forward toward the goal of an economically feasible process for capture of CO_2 from stack gases.

Proj311.pmd

PROJECT facts

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

Sequestration

01/2005

CARBON DIOXIDE RECOVERY FROM COMBUSTION FLUE GAS USING CARBON-SUPPORTED AMINE SORBENTS

CONTACTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

Philip Goldberg
Project Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-5806
philip.goldberg@netl.doe.gov

Marek Wojtowicz
Advanced Fuel Research, Inc.
87 Church Street
East Hartford, CT 06108
860-528-9806
marek@AFRinc.com

Background

In Phase I, Advanced Fuel Research, Inc. will initiate development of a novel sorbent for the removal of carbon dioxide from combustion/incineration flue gas. The sorbent, based on amines supported on low-cost activated carbon, will be produced from scrap tires. Liquid-based amine systems are limited to relatively low concentrations to avoid corrosion. Corrosion should not be a problem with a supported amine.

Primary Project Goal

The primary goal of this project is to develop a process using a supported amine for CO_2 recovery that exhibits better system efficiency, lower cost, and less corrosion than current liquid amine-based processes.

Objectives

The objective is to develop a process using a supported amine as a sorbent. Such a process should avoid some of the problems inherent in liquid-phase amine processes.

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

Advanced Fuel Research, Inc.

COST

Total Project Value
$99,969

DOE/Non-DOE Share
$99,969/$0

Benefits

The United States has set a goal of reducing the CO_2 emissions intensity of economic activity (pounds of CO_2 emitted per dollar of GDP) by 18% by 2012. In order to meet this goal, new CO_2 capture processes need to be developed. Although existing processes are technically capable of recovering CO_2 from stack gases, they are too expensive to be deployed without seriously impacting our economy. If successful, this project could advance our efforts to achieve our CO_2 emissions goal.

PROJECT facts

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

Sequestration

01/2005

NETL

MULTIPLE-INPUT DATA ACQUISITION SYSTEMS (MIDAS) FOR MEASURING THE CARBON CONTENT IN SOIL USING INELASTIC NEUTRON SCATTERING

CONTACTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

John Litynski
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-1339
john.litynski@netl.doe.gov

Michael Momayezi
X-Ray Instrumentation Associates
8450 Central Ave
Newark, CA 94560
540-494-9020
Momayezi@xia.com

Background

It has been demonstrated that Inelastic Neutron Scattering (INS) can be used to measure the carbon content of soil, rapidly in situ and non invasively. In Phase I, X-Ray Instrumentation Associates will initiate the development of a new, non-invasive technology for static and dynamic in-situ carbon monitoring in soils that will speed up the rate of analysis at reduced cost and improved accuracy. Specifically, X-Ray Instrumentation Associates will upgrade an existing exploratory system developed at Brookhaven National Laboratory (BNL) by adding novel multichannel data acquisition electronics and conducting performance evaluations that will aid in the design of a commercial prototype in Phase II.

Primary Project Goal

The primary goal of this project is to develop a low power, compact INS system which is compatible with field deployment.

Objectives

The objective of this project is to upgrade an existing exploratory INS system at BNL by incorporating new multichannel data acquisition electronics to produce a device that is small, low-power, and compatible with field deployment.

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

X-Ray Instrumentation Associates

Brookhaven National Laboratory

COST

Total Project Value

$100,000

DOE/Non-DOE Share

$100,000/$0

Benefits

The improvement to the existing system of adding an array of gamma ray detectors promises to increase sampling volume and improve accuracy while reducing measurement time. Such a system would greatly improve the ability to verify carbon sequestration in terrestrial ecosystems.

Project 321.pmd

PROJECT facts

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

Sequestration

01/2005

INSTRUMENTATION SYSTEMS FOR MONITORING AND VERIFYING CARBON SEQUESTRATION IN TERRESTRIAL SYSTEMS

Background

There is a need to develop an accurate, low-cost, airborne, remote-sensing technology that will directly determine terrestrial biomass and the carbon stored in aboveground vegetation. Zimmerman Associates will test a new technology, which uses a down-looking, very high frequency (VHF) synthetic aperture radar (SAR) that will provide a faster, more accurate, and less expensive method to conduct biomass and carbon surveys.

The proposed airborne VHF SAR system will be flown at 3,000 meters with a downward looking antenna. Radar pulses returned from the area at 150,000 pulses per second will be used to estimate biomass and carbon contained within the footprint of the radar. Phase I will investigate the use of a single VHF frequency between 30 and 80 MHz. The selected frequency will be used for field experiments to determine power and sensitivity levels required for radar operations. A preliminary design for an operational prototype will also be developed.

Primary Project Goal

The primary goal of the project is to develop an airborne remote sensing system that will have the ability to conduct carbon surveys at a rate of 300 square miles per day at a cost of $0.25 per acre with an accuracy of ±10%.

CONTACTS

Scott M. Klara
Sequestration Technology Manager
National Energy Technology Laboratory
626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236
412-386-4864
scott.klara@netl.doe.gov

John Litynski
Project Manager
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507
304-285-1339
john.litynski@netl.doe.gov

Patrick Johnson
Zimmerman Associates, Inc.
9302 Lee Highway
Fairfax, VA 22031
301-371-3584
pjohns@erols.com

CUSTOMER SERVICE

1-800-553-7681

WEBSITE

www.netl.doe.gov

PARTNERS

Zimmerman Associates, Inc.

COST

Total Project Value
$99,836

DOE/Non-DOE Share
$99,836/$0

Objectives

The objective of the project is to develop an airborne VHF (30-80 MHz) SAR system that, when flown at 3,000 meters with a downward looking antenna, can conduct biomass and carbon surveys within the radar's footprint.

Benefits

The project will provide a fast, accurate, low-cost method to conduct surveys of biomass and carbon stored in aboveground terrestrial ecosystems. This technology could significantly improve our ability to verify terrestrial carbon sequestration and improve our ability to use this natural sink as a method for reducing CO_2 emissions.

Carbon Sequestration Participants Index

Bold text indicates reference to Fact Sheet

Foster-Wheeler Development Corporation	OV-4, B-2, B-4, **B-11,** C-2, C-3, C-5**, C-30, C-31**
Fuel Cell Energy, Inc.	C-2, C-3, C-5, **C-44, C-45**
General Motors (GM)	**M-12**
Geo-Environmental Engineering	**S-9**
Geological Survey of Alabama	**S-10, S-11**
Harvard University	B-2, B-3, B-4, **B-23**
Idaho National Energy & Engineering Laboratory (INEEL)	OV-3, C-2, C-3, C-5, **C-11**, **C-18, C-19**
IEA	
Illinois State Geological Survey	R-3**, R-6, S-60**
Indiana University	B-2, B-3, B-4, **B-27, B-28**
Industrial Research Limited (IRL)	
Institute for Environmental Management	**N-5**
Jim Walter Resources	**S-11**
Kansas Geological Survey	N-2, N-3, N-4**, N-9, N-11, N-12**
Kentucky Geological Survey	**S-21**
Kinder-Morgan CO_2 Company	**M-8, M-24**
Lawrence Berkeley National Laboratory (LBNL)	OV-3, **C-11**, S-2, S-4, S-6, **S-13**, **S-28, M-6**
Lawrence Livermore National Laboratory (LLNL)	OV-3, **C-11**, S-2, S-3, S-4, S-5, S-6, S-7,**S-48, S-13, S-28**
Los Alamos National Laboratory (LANL)	OV-5, C-2, C-5, **C-9**, **C-18, C-19,** M-2, M-3, M-4, **M-12, M-23, M-25**, B-2, B-4, **B-13, S-68**
Louisiana State University	**C-15**
Massachusetts Institute of Technology (MIT)	OV-4, S-2, S-5, S-6, **S-37**, M-2, M-3, M-4, **M-14**
McDermott Technology, Inc.	**C-11**
Mead Westvaco	**S-43**
Media & Process Technology, Inc. (MPT)	OV-6, C-2, C-3, C-5, **C-16, C-17**
Montana State University	R-3, **R-13**
Monterey Bay Aquarium Research Institute (MBARI)	OV-3, S-2, S-6, **S-32**
Mountain Forest Products	**S-43**
National Energy Technology Laboratory (NETL) (*Major projects only)	**C-32 C-34, C-36, C-38, C-40, S-56, S-60, S-62, S-64, S-66, S-70, S-72, M-25, M-27**
Netherlands Institute of Applied Geoscience TNO	**C-11**, **S-29, S-60**, **S-61**
New Mexico Institute of Mining & Technology	R-3**, R-9**
New Mexico Tech University	**M-24**
Nexant	OV-3, C-2, C-3, C-5, **C-8**
NGO	
Norsh Hydro	**C-13**
Oak Ridge National Laboratory (ORNL)	OV-5, **C-11**, S-2, S-3, S-4, S-5, S-6, S-7, **S-13**, **S-28**, **S-30**, **S-50**, **S-54**, **S-55**
Ohio Coal Development Office	**S-27**
Ohio Geological Survey	**S-27**
Ohio State University	OV-5, **M-19, M-22, M-35**
Ohio University	OV-5, B-2, B-4, **B-7, B-8**
Oklahoma State University	OV-5, S-2, **S-8, S-9**
OPHIR Corporation	**M-25**
Pacific Northwest National Laboratory	OV-7, S-2, S-3, S-4, S-6, S-5, S-7, **S-27, S-35, S-55**
Pall Corporation	**C-19**
Pan Canadian Resources	**C-13**
Parsons Energy & Chemical Group	**C-22**

Bold text indicates reference to Fact Sheet

Parsons Power	**S-56**
Pecos Petroleum	**M-25**
Pennsylvania State University	S-2, S-6, **S-9, S-60**
Petroleum Technology Research Council (PTRC)	**M-6**
Physical Sciences, Inc,	OV-4, B-2, B-4, **B-5**
Plum Creek Timber	**S-43**
Praxair	OV-4, C-2, C-3, C-5, **C-6**, **C-22**
Princeton University	OV-5, C-2, C-3, C-5, **C-32, C-33**
Programme of Belize	**M-12**
Provinces of Saskatchewan and Alberta	**M-6**
Research Institute for Environmental Technology	**M-6**
Research Institute for Innovative Technology for the Earth (RITE)	
Research Triangle Institute (RTI)	OV-4, C-2, C-3, C-5, **C-14, C-15**
Sandia National Laboratory (SNL)	OV-5, M-2, M-3, M-4, **M-24**, **M-25**
Savannah River	
Schlumberger	**S-13, S-27**
Scientific Monitor	**C-11**
Shell	**C-13**
Shell CO_2	
Shell Oil Company	**C-19**
SIMTECHE	**C-8, C-9**
SINTEF	**C-11**
Solid Waste Association of North America	**N-5**
Southern States Energy Board	R-3**, R-7**
Stanford Research Institute	**C-11**
Stanford University	**C-11, S-29**
Statoil	**C-13, S-29**
Stephen F. Austin State University	OV-6, S-2, S-5, S-6, **S-40, S-41,M-12**
Strata Production Company	**M-24, M-25**
Süd Chemie	**C-34**
Suncor Energy	**C-13**
TDA Research. Inc.	**C-11**
Tennessee Valley Authority (TVA)	OV-6, **S-46**
Terra Tek	
Texaco	**M-12**
Texas American Resources	**S-13**
Texas Bureau of Economic Geology	
Texas Engineering Experiment. Station	OV-5, S-2, S-4, S-6, **S-22**
Texas Tech University	OV6, **C-11**, S-2, S-6, **S-14**
The Commonwealth Scientific & Industrial Research Organization (CSIRO)	**S-60**
The Institute of Ocean Science	
The Nature Conservancy	OV-7, M-2, M-3, M-4, **M-11**
The Norwegian Institute of Water Research	
The Society of Wildlife Research (SPVS)	**M-12**
Tie-Line Technology	**C-11**
Trimeric Corporation	SB-2**, SB-3**
TXU (Texas Utilities)	**S-41**
U.S. Department of Energy's Office of Fossil Energy (FE)	
U.S. Geological Survey (USGS)	**S-57, M-18**

Bold text indicates reference to Fact Sheet

University of Alberta	**M-6**
Universidad Austral de Chile	**M-12**
University of Alabama	**S-11**
University of California at St. Louis Obispo	
University of California, San Diego	OV-3, M-2, M-4, **M-9**
University of Cincinnati	**C-11**
University of Colorado	**C-19**
University of Georgia Research Foundation	B-2, B-3, B-4**, B-29**
University of Hawaii	
University of Kansas	OV-4, **M-17, M-18**
University of Kentucky	OV-4, S-3, S-4, S-5, S-6**, S-20, S-44**
University of Kentucky Research Foundation	OV-4, S-2, S-6, **S-20**
University of Massachusetts	OV-4, S-2, S-5, S-6, **S-38**
University of Minnesota	B-2, B-3, B-4, **B-15, B-28**
University of New Mexico	B-2, B-3, B-4, **B-17**
University of North Dakota	R-3**, R-17**
University of Notre Dame	B-2, B-3, B-4**, B-21**
University of Oklahoma	**S-60**
University of Pittsburgh	**S-56, S-60, S-62**
University of Regina	**M-6**
University of Southern California	**C-17**
University of Southern Illinois	**S-60**
University of Southern Maine	
University of Texas	S-4, **S-57**
University of Texas at Austin	OV-6, C-2, C-3, C-5, **C-24**, S-2, S-6, **S-12**, **S-13, S-29**
University of Utah	OV-6, S-2, S-4, S-6, **S-24**
University of Washington at St. Louis	**S-33**
UOP LLC	B-2, B-3, B-4**, B-19**
US Department of Agriculture Forest Service	**S-44**
US Department of Energy Office of Science	
US Department of Interior Office of Surface Mining	
Utah State University	**C-11**, S-4
Velocys, Inc	OV-5, N-2, N-3, N-4, **N-9**
Virginia Polytechnic Institute	OV-7, S-3, S-6, **S-42, S-55**
Virginia Technical University	**M-12**
West Virginia University	**S-27, M-25**
Westvaco	
Winrock International Institute of Agricultural Development	**M-12**
X-Ray Instrumentation Associates	SB-2, **SB-9**
Yolo County	OV-3, N-2, N-3, N-4, **N-5**
Zimmerman Associates	SB-2, **SB-11**

Bold text indicates reference to Fact Sheet