## *Project Archive - Sequestration*

| Project Title | Primary Contractor | Project End Date | Fact Sheet Listing |
|---|---|---|---|
| Unmineable Coalbeds & Enhancing Methane Production Sequestering Carbon Dioxide | Oklahoma State University/Penn State University | 6/15/2003 | PAS-3 |
| Geologic Screening Criteria for Sequestration of $CO_2$ in Coal: Quantifying Potential of the Black Warrior Coalbed Methane in Fairway, Alabama | Alabama Geologic Survey | 10/5/2003 | PAS-5 |
| Analysis of Devonian Black Shale in Kentucky for Potential Carbon Dioxide Sequestration and Enhanced Natural Gas Production | University of Kentucky Research Foundation | 9/30/2005 | PAS-9 |
| Carbon Capture and Water Emissions Treatment System (CCWESTRS) at Fossil Fueled Electric Generation | Tennessee Valley Authority | 8/30/2005 | PAS-11 |
| An Investigation of Gas/Water/Rock Interactions & Chemistry | NETL | 2005 | PAS-13 |
| Ocean Sequestration | NETL | 2005 | PAS-15 |
| Enhancement of Terrestrial Carbon Sinks Through Reclamation of Abandoned Mine Lands in the Appalachians | Stephen F. Austin State University | 9/19/2006 | PAS-17 |
| Restoring Sustainable Forests on Appalachian Mined Lands for Wood Products, Renewable Energy, Carbon Sequestration, and Other Ecosystem Services | Virginia Polytechnic Institute and State University | 1/31/2006 | PAS-19 |
| Carbon Sequestration on Surface Mine Lands | University of Kentucky | 3/2006 | PAS-21 |
| Gas/Water Interactions Project and the NETL Water Tunnel Facility and Hydrate Laboratory | NETL | 2007 | PAS-23 |
| Geology and Reservoir Simulation for Coal Seam Sequestration | NETL | 2007 | PAS-27 |
| Maximizing Storage Rate and Capacity and Insuring the Environmental Integrity of Carbon Dioxide* | Texas Tech University | 8/1/2004 | * |
| Reactive, Multi-phase Behavior of $CO_2$ in Saline Aquifers Beneath the Colorado Plateau* | University of Utah | 6/30/2005 | * |
| Exploratory Measurements of Hydrate and Gas Compositions* | LLNL | 9/30/2003 | * |
| Enhanced Practical Photosynthesis Carbon Sequestration* | ORNL | 9/30/2003 | * |
| Geology and Reservoirs Simulation for Brine Field* | NETL | 2005 | * |

(UCR projects not included)

* Factsheet Not Available

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PROJECT facts

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

Sequestration

03/2006

# UNMINABLE COALBEDS AND ENHANCING METHANE PRODUCTION SEQUESTERING CARBON DIOXIDE

## CONTACTS

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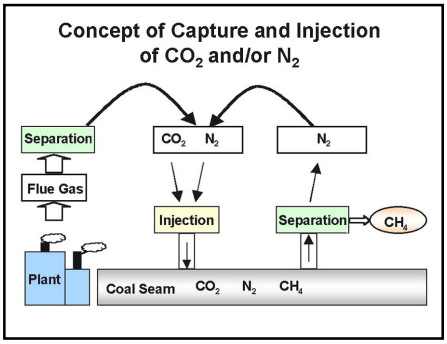
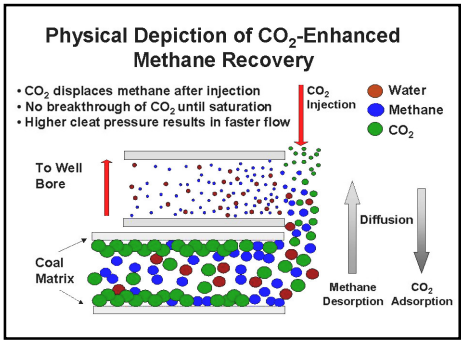
## Background

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 led an effort to investigate and test the ability of injected carbon dioxide to enhance coalbed methane production. The specific focus of this project was to investigate the competitive adsorption behavior of methane, $CO_2$, and nitrogen on a variety of coals. Measurements were focused on the adsorption of the pure gases, as well as mixtures. Data was taken from 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 were developed to describe accurately the observed adsorption behavior. The combined experimental and modeling results were generalized to provide a sound basis for performing reservoir simulation studies. These studies evaluated the potential for injecting $CO_2$ or flue gas into coalbeds to simultaneously sequester $CO_2$ and enhance coalbed methane (CBM) production.



## PARTNERS

Oklahoma State University

Penn State University

Geo-Environmental Engineering
State College, PA

## COST

**Total Project Value**
$876,175

**DOE/Non-DOE Share**
$820,649 / $55,526

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## CUSTOMER SERVICE

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## WEBSITE

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# Primary Project Goal

The overall goal of this project was 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

Completion of this project has contributed the following knowledge to the field of adsorption of coalbed gases for CBM production and $CO_2$ sequestration:

- Significantly expanded database for adsorption, including valuable data on:
  - A variety of pure, binary, and ternary gas mixtures
  - Eight different coal matrices and activated carbon
  - Effects of moisture on adsorption behavior for selected systems
- An adsorption modeling capability based on theory, including development of:
  - Several state-of-the-art models for representing adsorption equilibrium of pure fluids and mixtures within their experimental uncertainties
  - Generalized and matrix-calibrated models to provide accurate predictions within one to three times the experimental uncertainties
- Improved models to estimate coal capacity for coalbed gases based solely on readily accessible coal characterizations parameters
- Improved computational capabilities, including robust algorithms for solving adsorption equilibrium for a variety of models
- An improved pure-fluid and mixture compressibility factor EOS model which is required for CBM adsorption measurements
- Dissemination of the above accomplishments to the scientific and engineering community through a series of technical reports, presentations, and journal publications.

# Objectives

The objective of this effort was to develop, test and investigate the ability of coal to enhance coalbed methane production while sequestering carbon dioxide by adsorption on the surface of various U.S. coals.

# Benefits

This project significantly enhanced the understanding of multilayer adsorption of near critical and supercritical components on heterogeneous surfaces. The data and models developed permitted 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.

Project212.pmd

PROJECT facts

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

Sequestration

03/2006

# GEOLOGIC SCREENING CRITERIA FOR SEQUESTRATION OF $CO_2$ IN COAL: QUANTIFYING POTENTIAL OF THE BLACK WARRIOR COALBED METHANE FAIRWAY, ALABAMA

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## 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 number of 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 9$^{th}$ 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 conducted research to determine the amount of $CO_2$ that can be stored in the Black Warrior coalbed methane region of Alabama.

## Primary Project Goal

The primary goal of this project was 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.

## 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.

## Conclusion

Coalbed methane formations in the upper Pottsville Formation of the Black Warrior basin are extremely heterogeneous, and this heterogeneity must be considered to screen areas for the application of $CO_2$ sequestration and enhanced coalbed methane recovery technology. Major screening factors include stratigraphy, geologic structure, geothermics, hydrogeology, coal quality, sorption capacity, technology, and infrastructure. Applying the screening model to the Black Warrior basin indicates that geologic structure, water chemistry, and the distribution of coal mines and reserves are the principal determinants of where $CO_2$ can be sequestered. By comparison, coal thickness, temperature-pressure conditions, and coal quality are the key determinants of sequestration capacity and the quantity of coalbed methane that can be accessed through enhanced recovery operations.

Upper Pottsville coal beds are preserved in a series of flooding-surface-bounded depositional cycles of fluvial-deltaic origin that span 1,500 to more than 4,000 feet of section. More than 20 coal beds have been completed in some wells. Coal beds as thin as 1 foot are commonly completed, and net completable coal thickness ranges from about 10 to more than 70 feet.

Because coal and coalbed methane resources are dispersed widely through a thick section, multiple zone technology will need to be developed and applied to realize the potential of upper Pottsville strata for $CO_2$ sequestration and enhanced coalbed methane recovery.

Compressional folds and extensional faults are abundant in the Black Warrior basin, and these structures have a significant effect on the production performance of coalbed methane wells. Normal faults are major reservoir discontinuities, and trans-stratal fracture systems associated with these faults pose potential leakage risks. Therefore, $CO_2$ sequestration and enhanced recovery operations should avoid fault zones. Strata-bound joint and cleat systems are developed between the fault zones, and these fracture systems tend to favor the development of reservoir compartments around individual coal zones that favor bed-parallel flow over crossformational flow.

Permeability, water chemistry, and temperature-pressure conditions are the key hydrologic and geothermal variables to be considered when screening coalbed methane formations. Permeability-depth relationships in the Pottsville Formation favor sequestration and enhanced recovery efforts in coal shallower than 2,000 feet. Water chemistry is a fundamental control on where sequestration technology can be applied because of UIC regulations. Fresh-water plumes along the southeast margin of the Black Warrior basin contain water with TDS content less than 3,000 mg/L, and current UIC regulations

prohibit underground injection into water that fresh. Most of the coalbed methane fields contain water with 3,000 to 10,000 mg/L TDS, and an aquifer exception can be obtained to facilitate enhanced hydrocarbon recovery programs (Class II UIC). Water with TDS content higher than 10,000 mg/L is common in some of the southwestern coalbed methane fields, and in these areas, $CO_2$ can be injected into coal without enhanced hydrocarbon recovery (Class I UIC).

Coalbed methane formations in the Black Warrior basin are normally pressured to underpressured, and geothermal gradients are generally between 8 and 15°F per 1,000 feet. Temperature correlates negatively and significantly with the sorption capacity of coal and must therefore be considered in regional estimates of sequestration capacity. Reservoir pressure has been depleted by prolonged dewatering associated with coalbed methane production. Beyond a depth of 2,480 feet, $CO_2$ will become a supercritical fluid if the reservoir returns to a normal hydrostatic pressure gradient. Supercritical $CO_2$ can weaken and react with coal, and rapid volumetric changes at the critical point raise some concerns about reservoir integrity and wellbore integrity. However, coal has stored supercritical $CO_2$ under natural conditions over geologic time.

The most important coal quality parameters determining how much gas can be stored in coal are ash content and rank. Ash content correlates negatively with sorption capacity, but the utility of ash content for regional assessment of sequestration and enhanced recovery potential is limited because ash data are too variable to predict between data points. Coal rank correlates highly with gas sorption capacity and is a regionalized variable that can be projected between data points with confidence. For these reasons, rank and reservoir temperature are key variables required to quantify the sequestration potential of coalbed methane formations in the Black Warrior basin.

The sorption capacity per unit weight of coal in the Black Warrior coalbed methane fairway is influenced strongly by rank and reservoir temperature, whereas the sorption capacity per unit area of coal in the upper Pottsville Formation is influenced strongly by coal thickness. At 100 to 350 psi, upper Pottsville coal can adsorb between 250 and 700 scf/t and between 5 to 80 MMcf/ac of $CO_2$ on an as-received basis. Estimated at a modest pressure of 50 psi, unswept coalbed methane resources range from 40 to 100 scf/t and 1 to 7 MMcf/ac.

Numerous technological and infrastructural variables must be examined to screen areas for $CO_2$ sequestration and enhanced coalbed methane recovery. Critical variables for the Black Warrior coalbed methane fairway include proximity to coal-fired power plants, the design and maturity of coalbed methane fields, and pipeline infrastructure. Identifying the locations of underground coal mines, coal reserves, unplugged core holes, and communities are also important components of a screening strategy. Two coal-fired power plants are at the northern margin of the coalbed methane fairway, and a new plant is planned for the central part of the fairway. Most of the fairway is reaching maturity, although infill drilling and recompletion programs in some fields limit where demonstration and enhanced recovery programs should be sited. Coal mines and coal reserves are scattered through the northern part of the coalbed methane fairway and should be protected from sequestration activities.

Coal-fired power plants serving the Black Warrior basin in Alabama emit approximately 31 MMst (2.4 Tcf) of $CO_2$ annually. The total sequestration capacity of the Black Warrior coalbed methane fairway at 350 psi is about 189 MMst (14.9 Tcf), which is equivalent to 6.1 years of greenhouse gas emissions from the coal-fired power plants. Applying the geologic screening model indicates that significant parts of the coalbed methane fairway are not accessible because of fault zones, coal mines, coal reserves, and formation water with TDS content less than 3,000 mg/L. Excluding these areas leaves a sequestration potential of 60 MMst (4.7 Tcf), which is equivalent to 1.9 years of emissions. Therefore, if about 10 percent of the flue gas stream from nearby power plants is dedicated to enhanced coalbed methane recovery, a meaningful reduction of $CO_2$ emissions can be realized for nearly two decades. If the fresh-water restriction were removed for the purposes of $CO_2$ sequestration, an additional 10 MMst (0.9 Tcf) of $CO_2$ could feasibly be sequestered. The amount of unswept coalbed methane in the fairway is estimated to be 1.49 Tcf at a pressure of 50 psi. Applying the screening model results in an accessible unswept gas resource of 0.44 Tcf. Removal of the fresh-water restriction would elevate this number to 0.57 Tcf. If a recovery factor of 80 percent can be realized, then enhanced recovery activities can result in an 18 percent expansion of coalbed methane reserves in the Black Warrior basin.

## 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/Non-DOE Share**
$ 789,565 / $ 608,503

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## CUSTOMER SERVICE

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## WEBSITE

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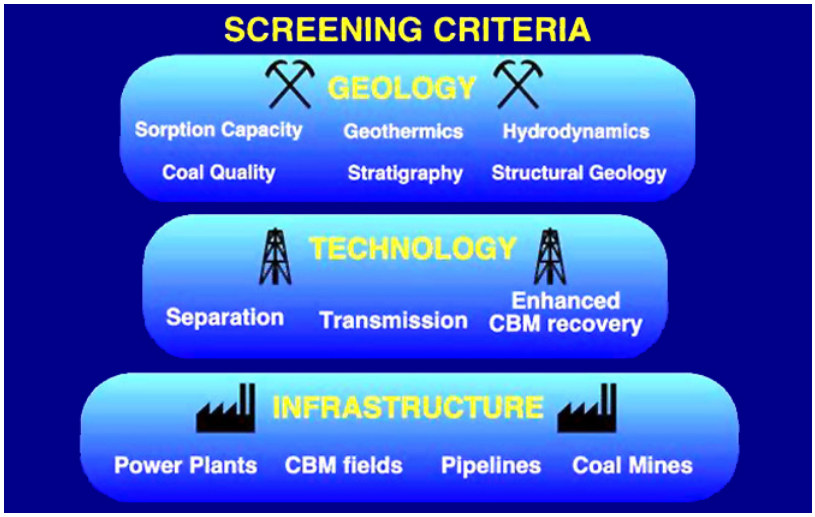
Results of this investigation indicate that the potential for $CO_2$ sequestration and enhanced coalbed methane recovery in the Black Warrior basin is substantial and can result in significant reduction of greenhouse gas emissions while increasing natural gas reserves. Application of the geologic screening model to the Black Warrior coalbed methane fairway indicates that sequestration and enhanced recovery operations are possible in nearly all coalbed methane fields, and the only areas that appear to be technically infeasible within those fields are areas with coal reserves and fault systems. Future work should focus on the development and implementation of demonstration programs that focus on determination of optimal $CO_2$ injection rates, quantification of sequestration and enhanced gas recovery efficiency, and monitoring and verification of sequestration activities.

## 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.*

Project211.pmd

PROJECT facts

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

Sequestration

03/2006

# ANALYSIS OF DEVONIAN BLACK SHALE IN KENTUCKY FOR POTENTIAL CARBON DIOXIDE SEQUESTRATION AND ENHANCED NATURAL GAS PRODUCTION

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## 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 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 $CH_4$ is stored within coal beds. It has been demonstrated in gassy a coal 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 $CH_4$ 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.

## Primary Project Goal

To test the hypothesis that organic-rich shales can adsorb significant amounts of $CO_2$ while releasing $CH_4$. 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

## PARTNERS

University of Kentucky Research Foundation

Kentucky Geological Survey

## COST

**Total Project Value**
$532,966

**DOE/Non-DOE Share**
$364,453 / $168,513

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## CUSTOMER SERVICE

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## WEBSITE

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# Accomplishments

- 43 samples and two advanced well logs (ECS) were acquired and analyzed for this project.
- $CO_2$ and $CH_4$ adsorption isotherms indicate $CO_2$ is adsorbed at 5.3 times the volume of $CH_4$.
- Log analysis indicates TOC content of the shale can be estimated from density log data.
- A linear relation developed between TOC and $CO_2$ adsorption data indicates TOC data can be used as a proxy to estimate adsorptive capacity of the shale.
- It was determined that within the Devonian shale of eastern Kentucky, the Lower Huron Member of the Ohio Shale has the greatest $CO_2$ adsorption capacity.
- Whole rock cores are more representative of in-situ conditions expected in the subsurface, but the low permeability of shale resulted in flow-through and adsorption isotherm experiments that took longer than expected.
- Limited data (one sample) suggests adsorption isotherm data determined from whole rock samples are comparable to that data derived from powdered drill cuttings.
- Limited data (four samples) from the Illinois Basin suggest the Devonian New Albany Shale has adsorption characteristics similar to those of the Ohio Shale of the Appalachian Basin.
- Estimates using the distribution of gas storage capacity of $CO_2$ from TOC data indicate a sequestration capacity of 6.8 billion tonnes in the five-county area of the Big Sandy Gas Field of eastern Kentucky.
- Assuming a conservative thickness weighted average adsorption capacity of 40 scf/ton (at 400 psia), as much as 28 billion tons total in the deeper and thicker portions of the Devonian shales in the Appalachian and Illinois Basins of Kentucky.
- Enhanced production of natural gas displaced by injected $CO_2$ would contribute to a long-term increase in the supply of what is considered a "greener" fuel.
- Adsorption data indicate that black, organic-rich gas shales can serve as targets for sequestration of significant volumes of anthropogenic $CO_2$.

# 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 this goal. This project has evaluated an option that has received relatively little attention—storing $CO_2$ in organic 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. Where the shales are not viable sequestration targets, data developed will assist in evaluating shales as seals for any deeper sequestration targets.

Project281.pmd

PROJECT facts

U.S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

Sequestration

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

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### WEBSITE

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# Carbon Capture and Water Emissions Treatment System (CCWESTRS) at Fossil-Fueled Electric Generating Plants


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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

# 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.

Proj187.pmd

### CONTACT POINTS

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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

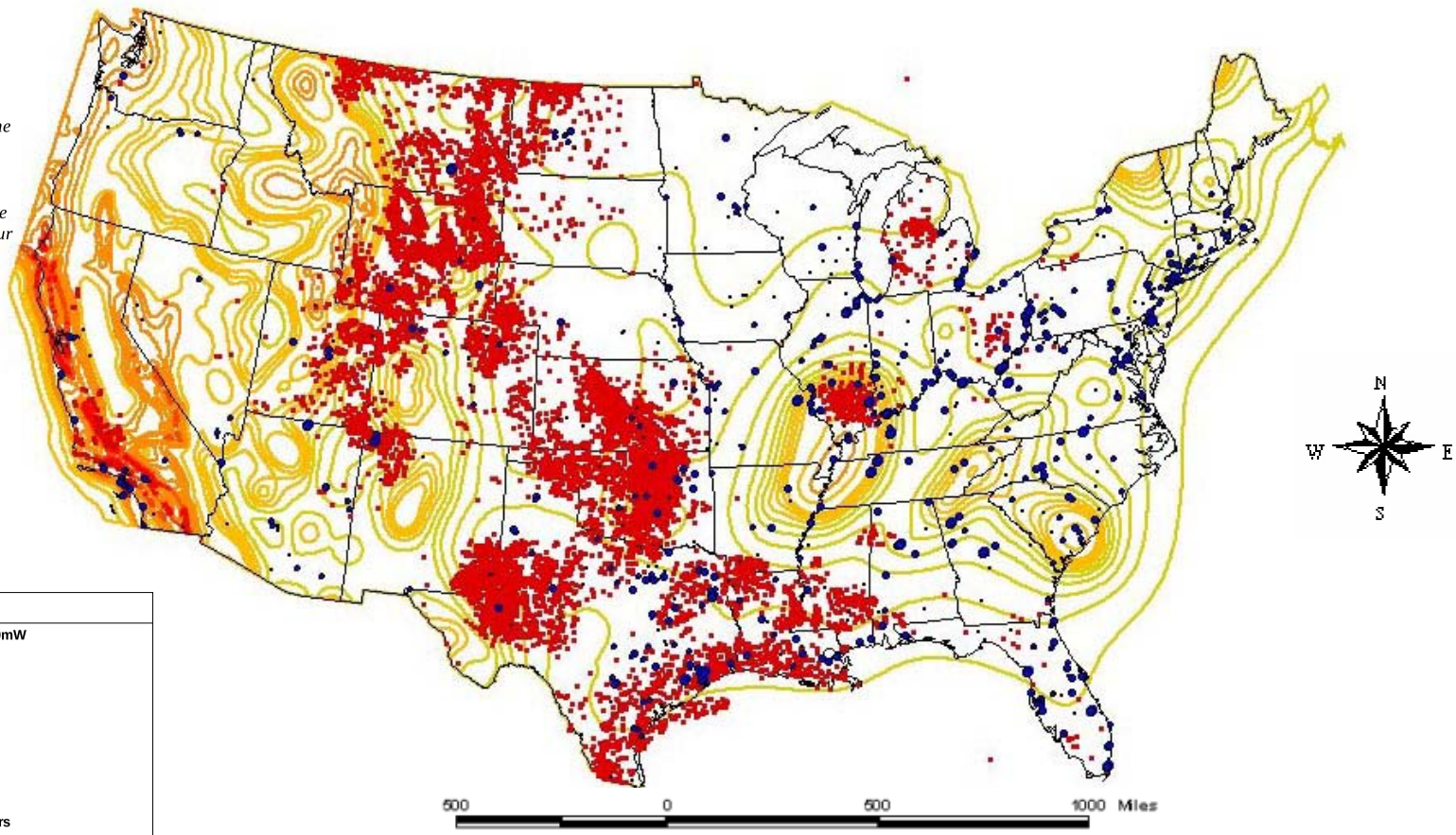
### WEBSITE

www.netl.doe.gov

# 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 1996 (EGRID96) and DOE/EIA 767.
Geological coverage 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

# OCEANIC SEQUESTRATION

## 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

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## WEBSITE

www.netl.doe.gov

## 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 $CO_2$.

# 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.*

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Proj189.pmd

PROJECT facts

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

Sequestration

03/2006

# ENHANCEMENT OF TERRESTRIAL CARBON SINKS THROUGH RECLAMATION OF ABANDONED MINE LANDS IN THE APPALACHIANS

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## Background

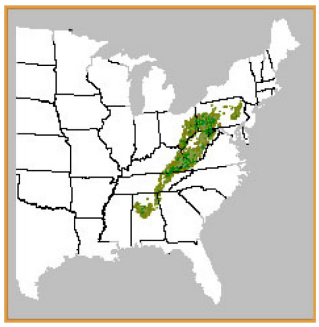
The continuing demand for fossil-fuel-based power and the associated rise in atmospheric carbon dioxide ($CO_2$) concentration will require the development of innovative ways to capture and store carbon. Terrestrial ecosystems, including both soil and the related vegetation, are recognized as significant 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.

The success of the project to determine optimum rotations on mine lands led to expansion of the project to model the top commercial tree species in the United States throughout the different ecosystems in the U.S.

## Primary Project Goal

This project will determine how to increase carbon sequestration in forests while increasing forest yields and providing other desirable ecosystem benefits.



*Abandoned Mine Lands in Appalachia*

## PARTNERS

Stephen F. Austin State University

Texas Utilities Electric Company

USDA Forest Service

## COST

**Total Project Value**
$1,595,146

**DOE/Non-DOE Share**
$1,097,670 / $497,476

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## CUSTOMER SERVICE

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## WEBSITE

**www.netl.doe.gov**

# 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 and other ecosystems throughout the United States

# Accomplishments

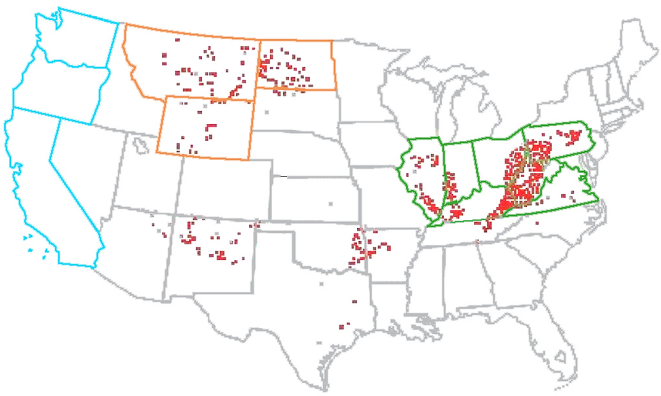
FORMOP, a combination of the U.S.D.A. Forest Service's growth and yield models and dynamic and economic programs, was used to simulate tree growth as a function of variables such as site quality, thinning frequency and intensity, and rotation length. Results indicate that costs of sequestering carbon 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.

The FORMOP model has been optimized to combine the economic and growth model into one program capable of analyzing millions of rotation cycles and stumpage prices to determine the best management schemes for the commercial trees species in the United States.

# 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.

Identifying the optimal management plans for each of the commercial tree species can add additional board feet and sequester an incremental amount of additional carbon.



*Approximately 1.6 million acres of land in the United States supports only limited vegetation due to past and present mining operations.*

Project230.pmd

PROJECT facts

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

Sequestration

03/2006

# RESTORING SUSTAINABLE FORESTS ON APPALACHIAN MINED LANDS FOR WOOD PRODUCTS, RENEWABLE ENERGY, CARBON SEQUESTRATION, AND OTHER ECOSYSTEM SERVICES

## CONTACTS

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## 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.
- To complete a cost benefit analysis of reforestation on these lands.
- To quantify the social and ecological benefits derived from these projects.

## PARTNERS

Virginia Polytechnic Institute and State University

Mead-Westvaco

Plum Creek Timber

Mountain Forest Products

The Nature Conservancy

U.S. Forest Service

## COST

**Total Project Value**
$629,381

**DOE/Non-DOE Share**
$494,400 / $134,981

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918-699-2000


## CUSTOMER SERVICE

**1-800-553-7681**

## WEBSITE

**www.netl.doe.gov**

# Accomplishments

A mine land site quality classification scheme was developed and some field-testing of the methods of implementation was completed.

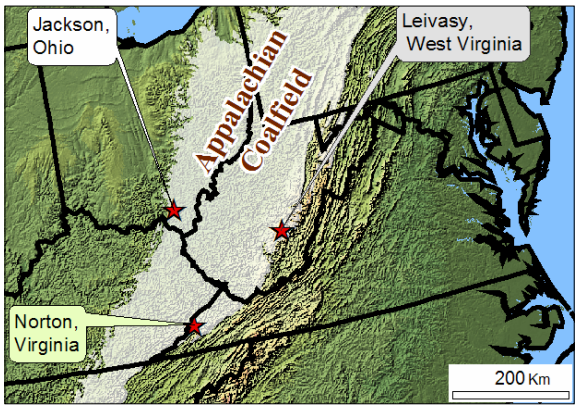
A preliminary economic analysis of the feasibility of reforestation with several different forest types and levels of management, has been completed.

To determine actual sequestration under different forest management scenarios, a field study was installed as a 3 x 3 factorial in a random complete block design with three replications at each of three locations, one each in Ohio, West Virginia, and Virginia. The treatments included three forest types (white pine, hybrid poplar, mixed hardwood) and three silvicultural regimes (competition control, competition control plus tillage, competition control plus tillage plus fertilization). Each individual treatment plot is 0.5 acres. Each block of nine plots is 4.5 acres, and the complete installation at each site is 13.5 acres.

Estimating the acreage of lands in Virginia, West Virginia, Kentucky, Ohio, and Pennsylvania mined under SMCRA and reclaimed to non-forested post-mining land uses that are not currently under active management, and therefore can be considered as available for carbon sequestration.

# 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.




*Location of Field Test Sites in Post-SMCRA Appalachian Coal Fields*

*White Pine, Hybrid Poplar, and Hardwood Mix Planted at Field Sites*

Project236.pmd

PROJECT facts

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

Sequestration

03/2006

# CARBON SEQUESTRATION ON SURFACE MINE LANDS

## 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 and the Office of Surface Mining and Reclamation Enforcement (OSMRE), 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.

*Bent Mountain , KY Mined Land Reclamation Site*

## CONTACTS

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## PARTNER

University of Kentucky

## COST

**Total Project Value**
$1,479,805

**DOE/Non-DOE Share**
$1,099,540 / $380,265

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## CUSTOMER SERVICE

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## WEBSITE

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# 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.

# Accomplishments

- Planting sites were identified at three mines in three widely separated locations.
- Experimental plots were established on previously reclaimed mined lands and mine lands being actively reclaimed. Different treatments included levels of tillage, herbicide application, seedling treatment, application of mulch, and amount of fertilization.
- Over 550 acres of mined lands have been planted with hardwood seedling project.
- More detailed studies to address specific questions pertaining to carbon flux are underway to determine the net amount of carbon sequestered in mine soils.
- Biomass from a chronosequence of reclaimed mined lands have been recovered to estimate the potential that this reclamation approach can achieve.
- Established a long-term research site demonstrating the OSMRE approved Forestry Reclamation Approach as a method to increase carbon sequestration rates.

# 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.

R & D facts

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

Sequestration

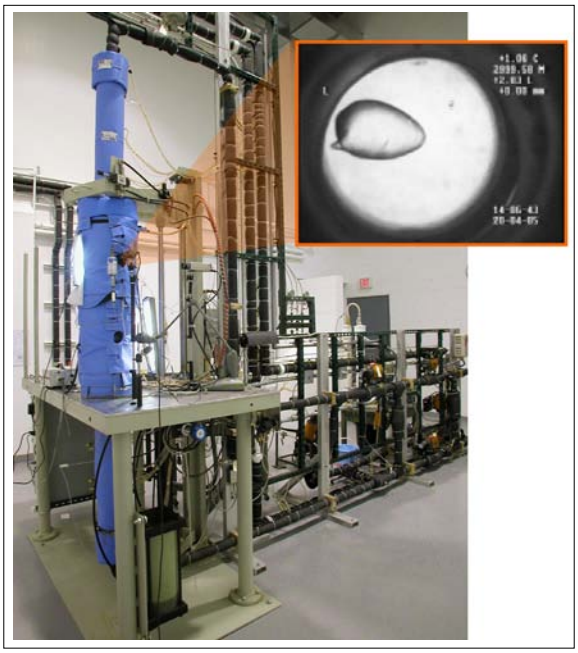
4/2006

# Gas/Water Interactions Project and the NETL Water Tunnel Facility and Hydrate Laboratory

## Background

The release of $CO_2$ into aqueous environments for the purposes of sequestration is possible in deep saline reservoirs, water-filled coal seams and in water-filled depleted oil or gas reservoirs. An unintentional release of $CO_2$ could also occur in the ocean or in deep lakes if the $CO_2$ in a geologic formation leaked into or was otherwise in contact with an overlying or adjacent body of water (e.g. the Sleipner project). Understanding the physical, chemical and spatial fate of $CO_2$ in such environments is necessary for predicting the success of the sequestration strategy and any potential environmental consequences associated with it.

The research on this project began in the early 1990s when the concept of direct deep ocean injection of $CO_2$ was a major topic of international investigation. Early work on obtaining fundamental information regarding the dissolution of $CO_2$ in both freshwater and seawater, and the potential impact of $CO_2$ hydrate on this process was performed in existing small-scale laboratory pressure vessels in the NETL Hydrate Laboratory. To overcome some limitations of the small pressure vessels, a High-Pressure Water Tunnel Facility (HWTF) was proposed in 1994. A Low-Pressure Water Tunnel Facility (LWTF) was first built to determine the geometric and flow requirements necessary for stabilization of a $CO_2$ drop using both a countercurrent flow of water and flow conditioning devices. The facilities are currently being used to perform research in $CO_2$ storage site monitoring and leak mitigation. The systems are also being used to perform research on methane hydrates as part of the National Methane Hydrates R&D Program.



*NETL's HWTF. Inset shows a hydrate-covered $CO_2$ drop that was stabilized in one of the observation and measurement windows by a countercurrent flow of seawater.*

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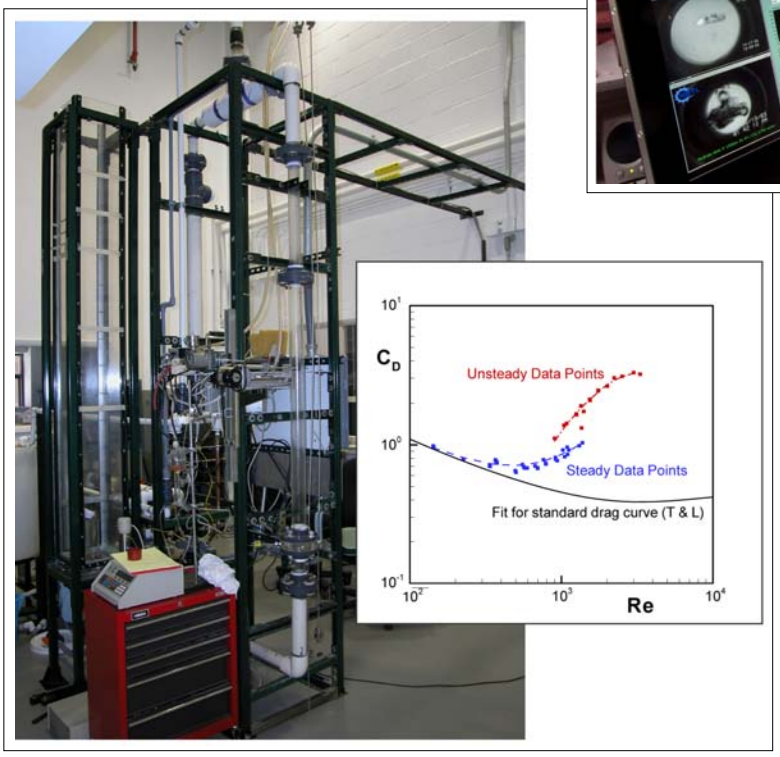
*Ron Lynn, Chief Engineer for the HWTF, shown at the console that controls operation of the HWTF and performs real-time measurement of objects stabilized in it. The HWTF is seen behind a 2.5-cm thick Lexan window.*




*The LWTF showing the flow loop in the center (clear tubing connected to a white PVC loop) and the static fluid tank to the left. Inset shows a drag curve determined for drops of castor oil, a liquid $CO_2$ surrogate, which exhibits a bifurcation in hydrodynamic behavior.*

The laboratory scale, high-pressure equipment in the Hydrate Laboratory and the LWTF have been used to provide important information on the formation and dissolution of $CO_2$ hydrate from dissolved $CO_2$, as well as the hydrodynamic behavior of particles that are analogous to liquid $CO_2$. The Hydrate Laboratory contains two environmental chambers that provide operational capabilities in the temperature range of -40 ºC to 200 ºC. One chamber is equipped with an explosion resistant interior that permits safe operation of flammable gases such as methane or natural gas. The pressure vessels currently available consist of two variable-volume viewcells with pressure ratings up to 135 MPa and a small-stirred autoclave with capacities of 50 and 100 mL. Precision syringe pumps are available for accurate metering of gases and liquids used in the research. The LWTF consists of a flow loop for testing the stability of liquid and solid objects in a countercurrent flow of water or other liquids compatible with the PVC and acrylic. It also contains a 2.4-m by 0.3-m square tank for examining the behavior, rising or falling, of liquid or solid particles in a static liquid medium. The HWTF consists of a 16-L flow loop with two windowed observation sections and various pumps for circulating and delivering liquids and gases.

All of the equipment is interfaced to National Instruments hardware and software. The HWTF also has extensive video capabilities that are interfaced to not only monitor and control the experiments but to perform real-time measurements of drop or particle size and motion. Research groups from Oak Ridge National Laboratory (ORNL) and the University of Massachusetts Lowell have successfully tested experimental concepts related to $CO_2$ sequestration in the HWTF. NETL researchers associated with these facilities are interested in pursuing other collaborations that would use the capabilities of this equipment to advance energy-related research.

## Primary Project Goal

The primary goal of the project and its related facilities is to provide scientific information useful for assessing the technical feasibility of $CO_2$ sequestration options where the $CO_2$ is released into water-filled environments either from engineered systems, leaks or natural seeps.

## Objectives

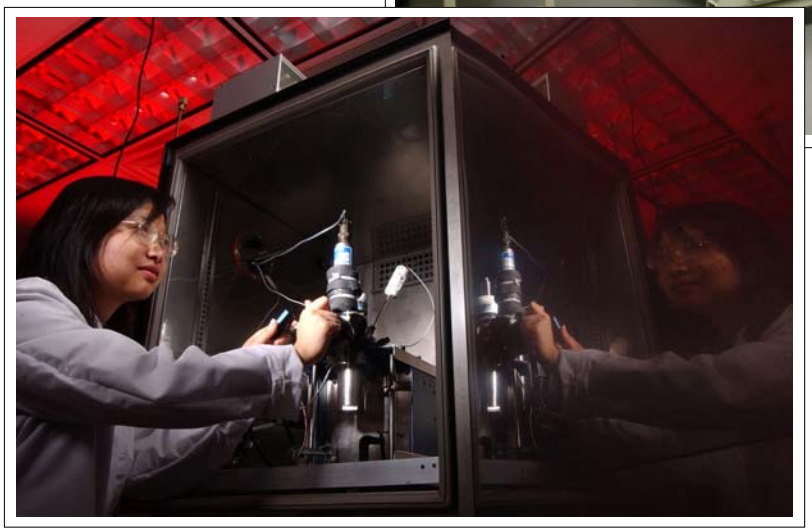
The objective is to provide a major facility for use in NETL's $CO_2$ sequestration activities that could also be used by others in this endeavor, as well as other energy research activities. The HWTF was NETL's first major $CO_2$ sequestration facility and has been successfully utilized as originally planned.

## Specific Accomplishments

The goal of using NETL's HWTF to obtain fundamental information on the behavior of how $CO_2$ drops in seawater was achieved. The experimental phase consisted of a two-year effort that determined the dissolution rates of over 500 individual $CO_2$ drops under simulated deep ocean conditions down to as low as 3000 m in depth. The impact of hydrate formation was also studied. The results are currently being analyzed and assembled into manuscripts that will describe the mass transfer and solubility of $CO_2$, both in the absence and presence of hydrate.

Experiments have also been completed in the LWTF that examined the hydrodynamic behavior of freely rising liquid drops that are low-pressure surrogates for liquid $CO_2$. This information has important implications in developing drag coefficient correlations that can be used to predict the free motion of $CO_2$ drops in aqueous environments. The results are being assembled into a manuscript.

*Eilis Rosenbaum and Yi Zhang performing experiments in the Hydrate Laboratory. The blue and white structures are the environmental chambers in which various reactors are contained for both $CO_2$ sequestration and methane hydrate research.*



*Yi Zhang preparing a small autoclave for an experiment involving $CO_2$ hydrates in the Hydrate Laboratory*

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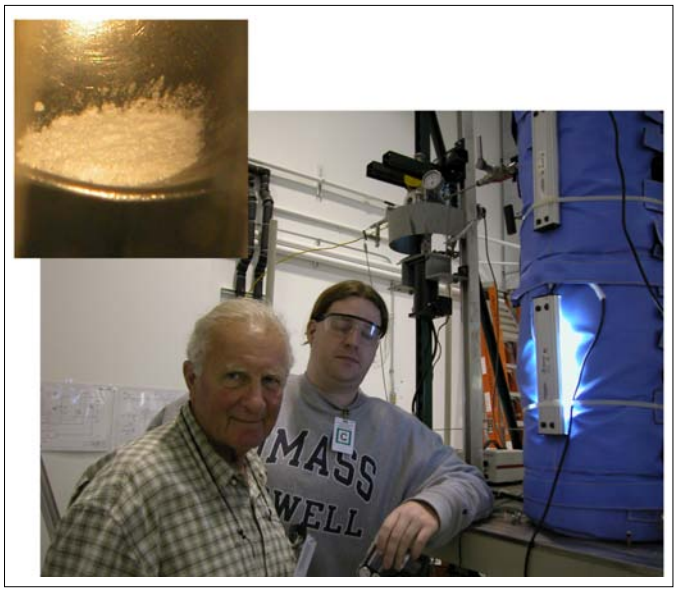
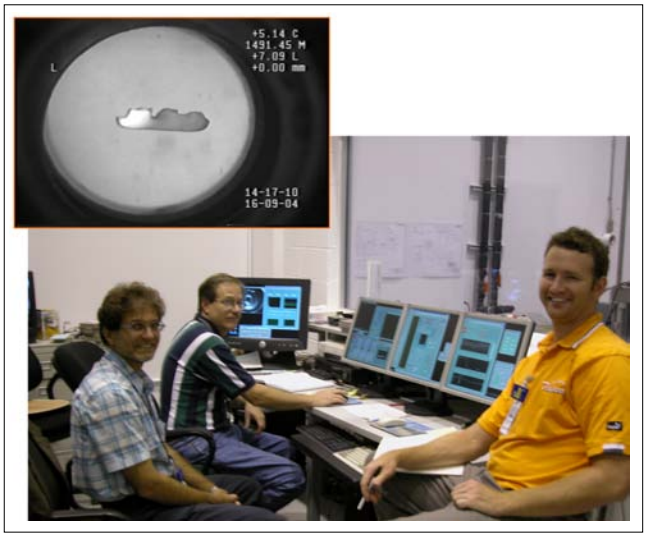
An important part of the research on this project is to understand the formation and dissolution of $CO_2$ hydrate in systems that contain dissolved $CO_2$. This factor, in addition to temperature and pressure, determines the potential formation conditions and stability of the hydrate. Precise interpretation of experimental results is made difficult by the rigorous demands for temperature uniformity and thorough mixing in the high-pressure system used for this research. After several years of work-testing various reactors and reactor configurations in the Hydrate Laboratory, a 100-ml stirred autoclave has been successfully configured and used to perform this work.



*Prof. Dan Golomb and Peter Swett from UML. Inset shows calcium carbonate coated $CO_2$ drops in the HWTF that were formed by their process.*

## Benefits

This project and its associated facilities have provided important information that will be useful to researchers and modelers in the area of $CO_2$ sequestration. Other research has been performed in the area of methane hydrates which is not covered in this factsheet. The HWTF was not only essential in this effort, but also demonstrated NETL's capabilities as a leader in carbon sequestration science. This facility and the others mentioned above are now being assessed for research in other areas of $CO_2$ sequestration and energy related research. Collaborative ideas with other researchers, whether formal or informal, are welcome.



*Dr. Costas Tsouris (left) and Dave Riestenberg (right) from ORNL along with Ron Lynn of NETL. Inset shows one of the hydrate/$CO_2$/seawater composite particles formed by the ORNL process in the observation and measurement section of the HWTF.*

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R & D facts

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

Sequestration

4/2006

# Geology and Reservoir Simulation for Coal Seam Sequestration

## Background

Unmineable coal seams are an attractive sink for power plant-generated carbon dioxide ($CO_2$), as this utilizes an otherwise uneconomic resource and makes possible the production of natural gas from coal seams. A coal seam sequestration model would help developers answer such questions as how much natural gas could be produced; how much, how fast, and under what operating conditions $CO_2$ could be sequestered; where to place injection and withdraw wells; and how much leakage could be expected.

As a result of past work, NETL currently has a suite of FORTRAN-based codes that generates a reasonable fracture pattern for a gas reservoir, FRACGEN, and solves the material balance for compressible fluid flow in the rock matrix and fractures of the reservoir, NFFLOW. Figure 1 shows a typical gas reservoir fracture pattern. Figure 2 shows the simulated fracture pattern for the same gas field but on a larger size, as generated by FRACGEN. Figure 3 compares NFFLOW's predictions for a well test to measured data.

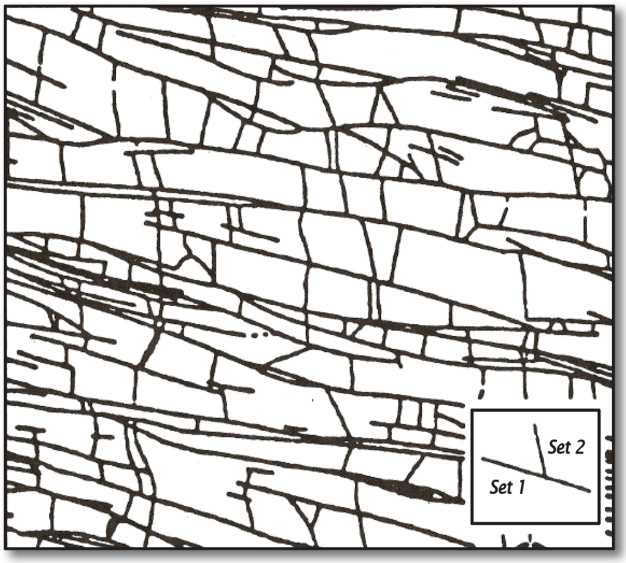


*Figure 1. Typical reservoir fracture pattern, MWX site.*

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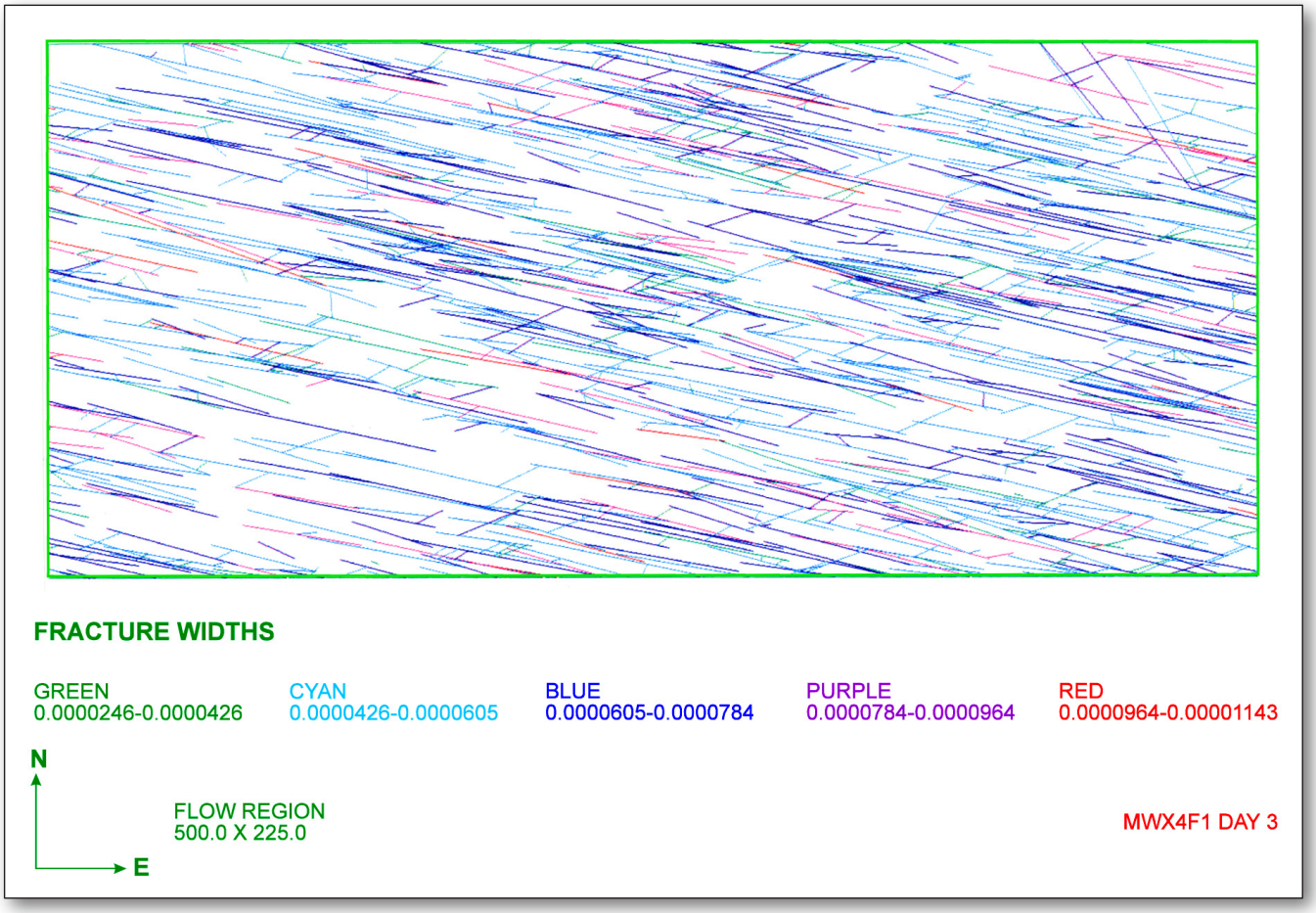


*Figure 2. This multicolored fracture pattern is a realization of NETL's model of the fracture network at the MWX site.The colors represent fracture aperture size.*

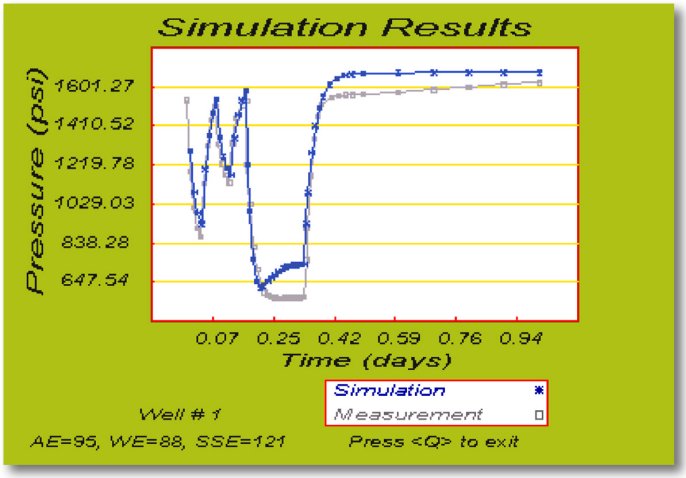


*Figure 3. Measured and simulated wellhead pressure.*

The "Geology and Reservoir Simulation for Coal Seam Sequestration" project undertaken by NETL's Geosciences Division intends to further advance the existing suite of reservoir simulation codes and adapt them to the problem of coal seam sequestration.

The current reservoir fracture network generator, FRACGEN, implements four Boolean models of increasing complexity through a Monte Carlo process that samples fitted statistical distributions for various network attributes of each fracture set. Termination and intersection frequencies can be controlled either implicitly or explicitly. Three models account for hierarchical relations among fracture sets, and two generate fracture swarming. Of course, the fracture network in a gas reservoir contains fewer but much longer and wider fractures than the system of cleats in a coal seam. FRACGEN will be modified to account for the fracture pattern in a coal seam.

Dual-porosity simulators are ubiquitously used for fractured reservoirs. However, networks and fractures themselves usually present large permeability aniso-tropies and heterogeneities across a range of scales. Thus, the scale of observation and spatial variability become critical issues in every investigation, and simple averaging, as required by conventional models, tends to lose utility. NETL has found that its explicit-fracture simulator, NFFLOW, is able to increase the accuracy and reliability of simulations for highly fractured reservoirs because it directly uses descriptions of such characteristics as fracture length, orientation, and aperture as obtained from well logs, outcrop analyses, and other geological data. In addition, by using the real gas potential for fluids, NFFLOW is able to treat compressible fluids. It has been developed with natural gas in mind, but with the appropriate equation of state, it could be used for flows of $CO_2$.

NFFLOW computes transient flow rates or bottom hole pressures according to user-specified pressure or rate sched-ules. It assumes that the reservoir is isothermal and one layer and that no flow occurs across the upper and lower boundaries of the reservoir. Each fracture is assumed to span the thickness of the reservoir, and the fracture network is assumed to contain no intersections formed by more than two fractures. Gravity effects are ignored, and the flow is single phase. The simulator handles wells that are horizontal or vertical and are either hydrofractured or intersected by natural fractures. All flow toward the well occurs through the fractures, except for drainage from the rock directly contacting the wellbore.

Volumetric flow within the fractures and wellbore is modeled as a linear function of the pressure difference between the recharge points and the fracture intersections. Darcy's Law is used to model the flow through the rock matrix to the recharge points in the nearby fractures. The resulting material balances at each fracture intersection and recharge point are discretized using finite difference and solved using a Newton-Raphson technique.

To become applicable to $CO_2$ flowing throughout a coal seam, NFFLOW must be modified to account for two-phase flow and to treat the coal matrix geometry realistically.

***NETL has found that its explicit-fracture simulator, NFFLOW, is able to increase the accuracy and reliability of simulations for highly fractured reservoirs***

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# Primary Project Goal:

The primary goal of this project is to create a tool that will help evaluate the suitability of a coal seam for sequestration and assist in optimum well placement.

# Objectives

The main objective of the project is to adapt existing gas reservoir simulation codes to simulate coal seam $CO_2$ sequestration.

# Accomplishments

- NFFLOW has been modified to account for more than one component in the gas phase.
- NFFLOW has been modified to include $CO_2$ adsorption on coal.

# Benefits

$CO_2$ sequestration in unmineable coal seams utilizes otherwise uneconomic resources, allows for the production of natural gas from the coal seams, and prevents $CO_2$ from entering the atmosphere.

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