U.S. Department of Energy • National Energy Technology Laboratory

Carbon Sequestration

Technology Roadmap and Program Plan - 2004

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

April 2004

Office of Fossil Energy

A MESSAGE TO OUR STAKEHOLDERS

Carbon sequestration continues to be one of the key technologies being pursued as a possible option to stabilize greenhouse gas concentrations in the atmosphere. The United States Department of Energy's (DOE) Sequestration Program remains committed to our leadership role in developing the technology base and infrastructure that would be required for future commercial deployments of carbon sequestration systems, if needed. The following are some highlights from the past year:

> *"Carbon sequestration has rapidly grown in importance to become on of the Administration's highest priorities. Our activities and our plans bear out the determination with which we are perusing the promise of carbon sequestration."*
>
> Secretary Spencer Abraham (November 2003)

- **Core R&D Program.** The Core R&D Program continued to make great strides toward meeting programmatic goals. Numerous technologies in the area of CO_2 capture are showing substantial potential for cost reduction and many of these technologies are approaching pilot-scale testing in the next few years. Sequestration field tests are progressing toward injection of small quantities of CO_2 into a saline formation and unmineable coal seam over the next two years. Terrestrial sequestration projects are conducting reforestation experiments on hundreds of acres of previously unproductive reclaimed mine lands. Substantial progress has occurred in the area of monitoring, mitigation & verification with the development/refinement of technologies to better understand storage stability, permanence, and characteristics of CO_2 migration. Non-CO_2 GHG mitigation concepts are entering the field testing stage of their development and many new breakthrough concepts have been added to the Program's research portfolio. More detail on latest Core R&D developments can be found in an updated project portfolio document which is available from the following weblink: http://www.netl.doe.gov/coalpower/sequestration/pubs/Carbon%20Sequestration%20Project%20Portfolio.pdf

- **Carbon Sequestration Leadership Forum (CSLF).** On June 25, 2003, Secretary Abraham and representatives from thirteen countries and the European Union signed the charter for the CSLF, "a framework for international cooperation in research and development for the separation, capture, transport, and storage of carbon dioxide." The CSLF has held several meetings and is pursuing a range of collaborative activities among the charter countries. Additional information on the CSLF can be found at the following weblink: http://www.cslforum.org/

- **Regional Partnerships.** On August 16, 2003, following a competitive solicitation, Energy Secretary Spencer Abraham named seven Regional Carbon Sequestration Partnerships. The seven partnerships, comprised of state agencies, universities, and private companies, are identifying CO_2 sources and potential sinks in their regions and are beginning to develop the infrastructure and framework for future deployment of sequestration technologies. Additional information on the Regional Partnerships can be found at the following weblink: http://www.netl.doe.gov/coalpower/sequestration/partnerships/

- **Breakthrough Concepts Research.** Over the past two years the Sequestration Program has been working with the National Research Council (NRC)/National Academy of Sciences (NAS) in an effort to bolster the high-risk/high-reward portion of the research portfolio. A joint workshop was held with prominent scientists to identify priority research areas, and in May 2003 the DOE announced a "Novel Approaches to Greenhouse Gas Management" solicitation for revolutionary and innovative research projects in the area of carbon capture. A competitive solicitation was conducted with support from the NRC/NAS, and seven awards were made in February 2004. The projects are varied and range from CO_2 conversion in underground formations to CO_2 capture with novel materials, such as ionic liquids and microporous metal organic frameworks. Additional information on the novel approaches awards can be found at the following weblink: http://www.netl.doe.gov/publications/press/2004/tl_novelapproaches_sel.html
- **Program Environmental Impact Statement (PEIS).** On October 31, 2003, Rita Bajura, Director of the National Energy Technology Laboratory (NETL), authorized the Carbon Sequestration Program to conduct an assessment of the environmental impact of programmatic activities. A PEIS was deemed necessary under the National Environmental Policy Act (NEPA). NETL has begun the PEIS process and is planning a series of public scoping meetings to be held in May and June of 2004. The PEIS is expected to require two to three years to complete. Additional information on the PEIS can be found at the following weblink: http://www.netl.doe.gov/coalpower/sequestration/eis/

Interaction with our stakeholders is critically important to the Sequestration Program. In 2004 the Program plans to engage stakeholders through the Third National Conference on Carbon Sequestration, Annual Project Merit Review Meeting, Regional Partnerships, the monthly carbon sequestration newsletter, conferences, and many other smaller outreach efforts. Through a cooperative partnership of industry, academia, and government, we have the best chance of success in developing viable carbon sequestration options.

This document is being updated annually to offer the latest snapshot of the DOE Sequestration Program. It is both a roadmap and a program plan. The roadmap portion identifies priority RD&D pathways, and the program plan presents the course of action to pursue these pathways. Public participation is strongly encouraged, and we invite readers to examine this document carefully and provide feedback to the contact persons listed at the back of this document.

CHAPTER I GLOBAL CLIMATE CHANGE AND THE ROLE OF CARBON SEQUESTRATION

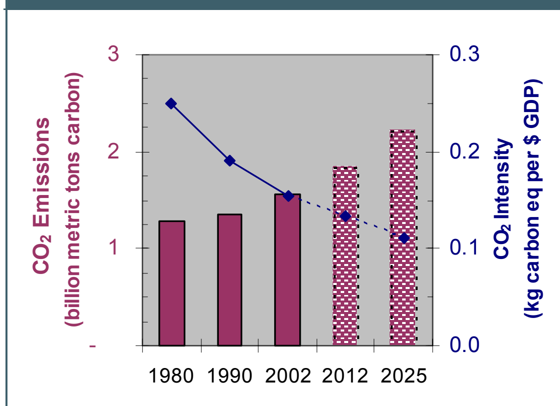
Global emissions of CO_2 from human activity have increased from an insignificant level two centuries ago to over twenty-four billion tons per year in 2003. Roughly half of the anthropogenic emissions are absorbed into oceans, forests, and other natural sinks, but the other half accumulates in the atmosphere, where the concentration of CO_2 is currently 379 ppm, 33 percent above pre-industrial levels, and rising at a rate of more than 1 ppm per year.

> "... there is a growing realization that existing energy technologies, even with substantial improvements, cannot meet the growing global demand for energy while delivering the emissions reductions necessary to stabilize atmospheric GHG concentrations. We need to develop and deploy globally "transformational" technologies—that is, revolutionary changes in the technology of energy production, distribution, storage, conversion, and use. Some examples include carbon sequestration, hydrogen, and advanced nuclear technologies."
>
> Harlan Watson
> U.S. State Department, Senior Climate Negotiator

CO_2 is a natural and important component of the atmosphere—animals exhale CO_2 and plants absorb it through photosynthesis. Also, CO_2, water vapor, and other gases exert a "greenhouse" effect that traps heat within Earth's ecosystem and which has, thus far, maintained the planet's temperate climate. Most scientists, including the Intergovernmental Panel on Climate Change (IPCC), recognize a danger that even a modest increase in the atmosphere's GHG effect could put the global climate out of balance and cause significant negative consequences for human health and welfare. It might be prudent to avoid continued increases in atmospheric GHG concentrations, but the cost to do so would be too high with existing technology. Effective policy must weigh the economic impacts of GHG emissions mitigation with the uncertainty surrounding the timing and severity of climate change impacts.

The response endorsed by the United States is to develop new technologies that provide energy services and economic prosperity while reducing GHG emissions. An appropriate metric to gauge progress for such an approach is the GHG intensity of economic activity (kg of CO_2 emitted per \$ of GDP). Figure 1 shows that, through normal technology progress, the CO_2 intensity of the U.S. economy decreased by 30 percent between 1980 and 2002. However, strong economic growth overwhelmed those gains, and the absolute emissions rate <u>increased</u> by 15 percent over the same time period. Atmospheric stabilization will require the average GHG intensity to be reduced at a rate faster than economic growth.

Figure 1. CO_2 Intensity of GDP and CO_2 Emissions in the United States



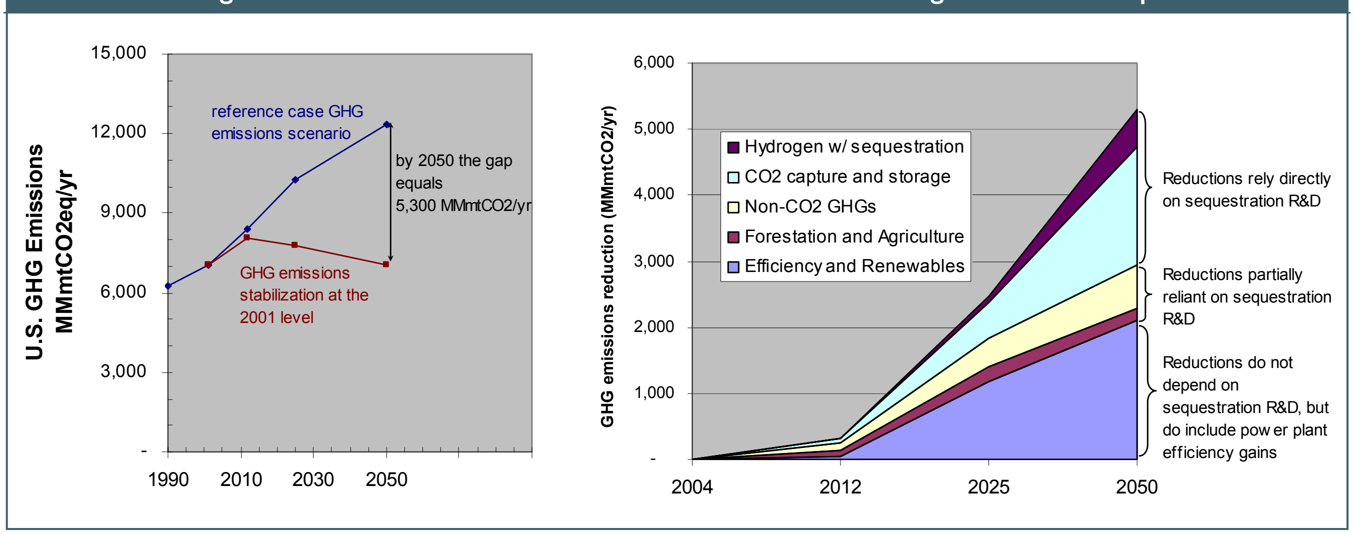
Fundamentally, there are three ways to reduce GHG emissions. The first is to use less energy while accomplishing the same economic work, either through more efficient machines, conservation, or simply being smarter about energy use. The second is to utilize carbonless energy sources, such as wind, solar, and nuclear, or reduced carbon energy sources, such as substituting natural gas for coal. Carbon sequestration is emerging as an important third option for greenhouse gas mitigation. Sequestration entails 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 stored in underground reservoirs, absorbed by trees, grasses, soils, and algae, or converted to rock-like solid minerals called carbonates. Options are also being explored to enhance dissolution of CO_2 in oceans; however, these options are still far from being considered viable due to the uncertainty regarding their potential environmental impacts.

The Sequestration Program has developed scenarios for domestic GHG emissions over the next fifty years. These scenarios help to quantify the potential need for advanced carbon sequestration technologies to stabilize greenhouse gas concentrations. The top line on the left graphic in Figure 2 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 2 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 2 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 2. U.S. GHG Emissions Scenarios . . . and Technologies to Fill the Gap



CHAPTER 2 CARBON SEQUESTRATION TECHNOLOGY ROADMAP AND PROGRAM PLAN

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 Global Climate Change Initiative (GCCI), as well as several National Energy Policy goals targeting the development of new technologies, and market mechanisms. 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.

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.

The Sequestration Program encompasses all areas of carbon sequestration, including CO_2 capture from utility and industrial point sources and the atmosphere; CO_2 storage in geologic formations, terrestrial ecosystems (as carbon), and oceans; technologies, techniques, and systems to track the fate of CO_2 in storage; and CO_2 conversion to either fuels or benign solids through biological or chemical means.

The roadmap and program plan is presented in 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. It includes:

- CO_2 capture
- Sequestration/storage
- Monitoring, mitigation & verification (MM&V)
- Breakthrough concepts
- Non-CO_2 GHG control

B. **Infrastructure Development** sets the groundwork for future carbon sequestration deployments. This section is focused on the seven recently-awarded Regional Partnerships.

C. **Program Management** discusses the program's approach to R&D management: industry/government partnerships, cost-sharing, education and outreach, environmental activities, and resource requirements.

Table 1 is a top-level roadmap for core R&D and infrastructure development.

Table 1. Top-level Carbon Sequestration Roadmap

	Goals	Pathways	Metrics for Success	
			2007	2012
CO_2 Capture	Lower the capital cost and energy penalty associated with capturing CO_2 from large point sources.	• Membranes • Advanced Scrubbers • CO_2 Hydrates • Oxy-fuel Combustion	50% reduction in cost of avoided CO_2 emissions from power plants compared to 2002 technology (based on pilot-scale performance).	Develop at least two capture technologies that each result in less than a 10% increase in cost of energy services.
Sequestration/ Storage	Improve understanding of factors affecting CO_2 storage permanence and capacity in geologic formations, terrestrial ecosystems and possibly the deep oceans. Develop field practices to optimize CO_2 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.
Monitoring, Mitigation, &Verification	Develop technologies and methodologies to accurately measure the amount of CO_2 stored in terrestrial ecosystems and geologic formations. Develop the capability to address any leaks of the stored CO_2 from various repositories.	• 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.	MM&V protocols that enable 95% of stored CO_2 to be credited as net emissions reduction. MM&V represents no more than 10% of the total sequestration system cost.
Breakthrough Concepts	Develop revolutionary approaches to CO_2 capture and storage that have the potential to address the level of reductions in greenhouse gas emissions consistent with long term atmospheric stabilization.	• 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.
Non-CO_2 GHGs	Develop technologies to mitigate fugitive methane from energy systems.	• Minemouth ventilation • Landfill gas recovery	Effective deployment of cost-effective methane capture systems.	Commercial deployment of at least two technologies from the R&D program.
Infrastructure Development	Develop the infrastructure required for wide scale deployment of sequestration concepts that are tailored to opportunities within specific regions of the United States and involve citizens, companies, and governments from those areas.	• Sequestration atlases • Project implementation plans • Regulatory compliance • Outreach and education	Phase I Regional Partnerships have developed action plans and completed regional atlases. Phase II partnerships begin pursing action plans and validation of sequestration concepts.	Phase II Regional Partnerships start to become self-sustaining and begin actively pursuing sequestration deployments.

A. Core R&D

Carbon Dioxide Capture

CO_2 capture is the separation of CO_2 from emissions sources or the atmosphere and the recovery of a concentrated stream of CO_2 that is amenable to sequestration or conversion.

Near and mid-term efforts are focused on capture of CO_2 from point sources, which can be broken into three broad categories: (1) flue gases from the combustion of fuels in air, (2) synthesis gases from oxygen-fired gasification, and (3) vents of highly-pure CO_2 from various industrial processes. Each is described below.

CO_2 Capture Goals

By 2007, show progress toward longer-term cost and efficiency goals for both pre- and post-combustion CO_2 capture, based on pilot-scale demonstration of new technology.

By 2012, develop, to the point of commercial deployment, systems for direct capture and sequestration of greenhouse gas emissions from fossil fuel conversion processes that protect human and ecosystem health and result in less than a 10% increase in the cost of energy services for gasification-based processes and a increase of less than 20% for combustion-based processes.

By 2018, develop, to the point of commercial deployment, systems for direct capture and sequestration of greenhouse gas and criteria pollutant emissions from fossil fuel conversion processes that result in near-zero emissions and approach no net cost increase for energy services, net of any value-added benefits.

Combustion. Air combustion is the traditional process for utilization of fossil fuels. Automobile engines, combustion turbines, and almost all coal and natural gas fired power plants operate on air combustion technology. CO_2 is exhausted from a conventional air-fired combustion system at near atmospheric pressure and in concentrations ranging from 3-15 volume%. The state-of-the-art technology for post-combustion CO_2 capture from flue gas is aqueous amine absorption. As a strong and selective chemical absorbent, amines are effective at capturing CO_2 from the dilute, low-pressure flue gas. However, they require significant energy for regeneration and deliver CO_2 at low pressure—the steam and electric load for amine-based CO_2 capture from a traditional pulverized coal power plant can increase the amount of coal consumed per net unit of power generated by 40 percent.

A different approach is to burn the fuel in oxygen rather than air and, thus, exhaust highly pure CO_2 (greater than 90 percent) which requires no separation. Currently, there are no commercial oxygen combustion power plants in operation. This is mainly due to the high cost of oxygen, which is produced by condensing air at cryogenic temperatures and then recovering oxygen by distillation. Another barrier to oxygen combustion is energy loss due to the large quantity of CO_2 exhaust that must be recycled to the oxygen boiler to maintain the combustion temperatures at a level that is compatible with boiler materials.

Gasification. In a gasification process, a carbonaceous fuel is thermally decomposed in the absence of oxygen to form a hydrogen-rich "synthesis gas" which can be converted to electrical energy through a variety of means (e.g., combustion turbine, electrochemical cell, or combined cycle). This synthesis gas contains 40-60 volume% CO_2 at pressures of several 100 psi, thereby, making it highly amenable to CO_2 capture before combustion or conversion. The state-of the-art for CO_2 capture from synthesis gas is a process involving liquid glycol solvent. The glycol is highly effective and can be used to capture both CO_2 and H_2S. However, the CO_2 is released at near atmospheric pressure and requires compression from 14-20 psi up to 2,000 psi, resulting in considerable increases in cost (but to a lesser extent than combustion processes).

Anthropogenic CO_2 Vents. Natural gas processing, ethanol and hydrogen production, cement manufacture, and a number of other industrial processes vent a nearly pure stream of CO_2 to the atmosphere as a normal part of their operation. These vents represent the lowest cost source of anthropogenic CO_2 and will likely be the first sources to be utilized for geologic sequestration deployment. In fact, the first marquee geologic sequestration project, at the Sleipner saline formation under the North Sea off the coast of Norway, utilizes a previously vented stream of CO_2 from an offshore natural gas processing platform (http://www.netl.doe.gov/coalpower/sequestration/pubs/mediarelease/SleipnerFactSheet4-19-02.pdf). Additionally, the Canadian Weyburn enhanced oil recovery project, which began injection in 2001, uses a high purity CO_2 vent stream from the Dakota Gasification Facility located in North Dakota, United States (http://www.netl.doe.gov/coalpower/sequestration/pubs/mediarelease/mr-101102.pdf). Importantly, there are many instances in which the advanced CO_2 capture technologies developed for flue and syngas streams can be applied to processes that vent CO_2 to increase vent pressure and decrease compression cost. This will lower the energy penalty and increase the net amount of emissions avoided through capture and storage.

The Carbon Sequestration Program Portfolio

A compendium of research project summaries, technical journals, planning documents, and other information pertinent to DOE's Carbon Sequestration Program has been assembled into a searchable PDF file. The "Program Portfolio" contains everything that interested parties need to know about carbon sequestration! Copies are available for download on the NETL website. http://www.netl.doe.gov/coalpower/sequestration/index.html

CD versions of the portfolio can be requested via email: Sequestration@netl.doe.gov

Capture R&D

The Sequestration Program is funding a relatively large number of CO_2 capture research projects at the laboratory to pilot scale. The range of technologies being explored includes liquid chemical absorbents, solid chemical absorbents, physical sorbents, solvents, membranes, hydrates, and combinations and hybrids of these options. Table 2 presents a synopsis the CO_2 capture technology pathways and supporting research efforts.

CO_2 capture efforts are focused on technologies that can offer a 90 percent or greater reduction in CO_2 emissions per net kWh or other unit of process output. Systems with that level of reduction will provide facilities that will support the concept of atmospheric greenhouse gas stabilization and will not require retooling in later years should more stringent GHG emissions limits come about. Technologies outside of the Sequestration Program are being pursued within the private sector, particularly retrofit technologies for air combustion power plants that offer a 30-60% reduction in CO_2 emissions per kWh at a low cost per unit of CO_2 capture. Such efforts compliment Sequestration Program activities and will likely serve as logical transition technologies to lower carbon intensity fuel conversion.

Although there are ample, high-purity CO_2 vent opportunities for the near term, CO_2 capture research efforts are aimed at enabling broad deployment that goes beyond these "low hanging fruit" near-term opportunities. Power plants represent roughly 40% of anthropogenic GHG emissions in the United States and roughly three quarters of total large point-source emission sources. Therefore, power plants are a natural focus for the Program, and the program's cost goal for capture is stated in terms of a percent increase in cost of electricity. The technologies being developed for capture are also applicable to a wide range of industrial sources, such as boilers, with minimal to no modification.

Technology progress to date is encouraging. Table 2 and the following paragraphs provide some examples, but are not intended to reflect the entire portfolio of projects. A complete description of all capture projects can be found at the following weblink:
http://www.netl.doe.gov/coalpower/sequestration/pubs/Carbon%20Sequestration%20Project%20Portfolio.pdf

For post-combustion capture, The University of Texas at Austin has developed an evolutionary improvement in solvent-based technology for capture of CO_2 from flue gas. The improved process uses a highly reactive solvent which absorbs CO_2 three times faster than monoethanolamine (MEA) and requires as much as 40 percent less energy per unit of CO_2 captured. This integrated system for CO_2 capture is undergoing pilot plant testing. (http://www.netl.doe.gov/publications/factsheets/project/Proj280.pdf)

Fluor Daniel, which has been funded by the Sequestration Program via the CO_2 Capture Project (CCP), also recently introduced an advanced amine CO_2 capture system for pulverized coal (PC) power plants, which involves aggressive heat integration that consumes only 1,700 Btu of low-pressure steam for each pound of CO_2 captured. By comparison, state-of-the-art amines in 2001 used 3,100 Btu/lb of CO_2. (http://www.netl.doe.gov/publications/factsheets/project/Proj185.pdf) The DOE Program is supporting development of several regenerable dry sorbent technologies for post combustion capture, and early lab-scale results indicate that some have potential to consume less energy than conventional aqueous amine processes. (http://www.netl.doe.gov/publications/factsheets/project/Proj198.pdf)

The integration of oxygen transport membranes (OTM) into oxy-fired boilers is being jointly developed by Praxair and Alstom Power. Using the heat generated in the furnace to produce steam will yield an economic advantage for boiler operation and CO_2 recovery. Boiler efficiency improvement is 14 percent compared to conventional boilers, including allowance for power associated with oxygen production. A conceptual design for a pilot scale (0.15-0.30 MW) boiler has been developed. (http://www.netl.doe.gov/publications/factsheets/project/Proj197.pdf)

For Integrated Gasification Combined Cycle (IGCC) power plants, a higher CO_2 partial pressure in the product gas stream opens up a broader range of technology options. Especially promising is the Hydrate Separation Process, a proprietary process being developed by SIMTECHE, LANL, and Nextant, which removes CO_2 from a shifted synthesis gas stream by forming CO_2 hydrates. The process concept has been demonstrated in a continuous-flow bench-scale unit, and further process development is underway that will lead to the construction of a pilot plant. Preliminary testing and analysis shows potential for capture cost 50 percent lower than comparable state-of-the-art systems. (http://www.netl.doe.gov/publications/factsheets/project/Proj196.pdf)

Also promising are concepts that integrate syngas water gas shift (WGS) reaction with CO_2 capture. The removal of CO_2 drives the thermodynamics of the shift reaction towards H_2 production and enhances overall system performance. Using leveraged funds from the Carbon Sequestration Program, the CCP has developed palladium membrane technology that integrates CO_2 separation with WGS. Laboratory-scale tests indicate that the new membrane could lower the capital cost of CO_2 capture by 50 percent and the energy penalty by up to 75 percent compared to a gasifier system using the state-of-the-art Selexol process for CO_2 capture. The Program's R&D portfolio contains other promising capture technologies. For example, polymeric membranes and high-temperature sorbents have the potential to exhaust CO_2 at several hundred pounds pressure, which would greatly lower the overall cost of capture and compression. (http://www.netl.doe.gov/publications/factsheets/project/Proj185.pdf)

Table 2. CO_2 Capture

Technology Roadmap			Supporting Program Activities	
Current State of the Art	Priority Research Pathways	Cross Cut Pathways	R&D Highlights	Program Goals *Lower cost and parasitic load*
Air Combustion Flue gas (10-15 psi, 12-18 vol% CO_2) is scrubbed with aqueous amine, which is regenerated with low-pressure steam diverted from a steam turbine. Captured CO_2 is produced at 10-15 psi. Cost of capture with current amine technology > $70/tonne of avoided CO_2 (decreases plant eff. from 40% to 24%), equivalent to a > 80% increase in COE for new construction.	Chemical sorbents: Aqueous amines Solid amines Ammonium carbonates Alkali carbonates Lithium-containing oxides	Heat integration Improved gasification or combustion efficiency Lower-cost oxygen Advanced gas/liquid contacting Integration of CO_2 capture with NO_x/SO_x/Hg/PM control	Palladium membranes: Laboratory scale testing shows potential for 50% cost reduction below state of the art glycol. Improved high-reactivity solvent shows promise of reducing energy requirements by up to 40% Engineering study shows that a combination of advanced heat integration, amines, and gas/liquid contacting has potential to reduce the net heat load for amines by 50%. Integration of OTM in furnace shows promise of improving the performance of oxy-fuel combustion. Laboratory-scale testing of new sorbents shows potential for 40% reduction in steam load per ton CO_2 captured compared to state-of-the-art amine. Use of CO_2 hydrates shows promise of significantly reducing the cost of CO_2 capture from syngas.	2004 pilot-scale demo of 75% reduction in CO_2 recycle requirements 2006 pilot scale demo of a 50% cost reduction below 2002 glycol for IGCC. 2008 Pilot scale demo of a 50% cost reduction below 2002 amine for a PC power plant. 2012 Develop at least four capture technologies that each result in less than a 10% increase in cost of energy services
Oxycombustion Cryogenic O_2 production. Minimum CO_2 recycle is 5 lb CO_2 per lb coal burned. 90% purity CO_2 is produced from the boiler at 10-15 psi. Oxygen combustion requires roughly three times more oxygen per kWh of electricity than gasification.	Oxygen transport membranes CFB designs without recycle Chemical looping			
IGCC Prior to H_2S removal, syngas is shifted to convert CO to CO_2 and H_2. H_2S and CO_2 removed from shifted syngas (50 psi, ~40 vol% CO_2) via glycol solvent in a single tower. Rich solvent flashed to recover CO_2 at 10-15 psi. Cost of capture with current glycol technology is > $25/ton of CO_2 avoided (plant efficiency reduced from 43% to 37%), equivalent to a > 25% increase in COE for new construction.	Physical sorbents: Selexol Rectisol Carbon Membranes: Ceramic Polymer Hybrid organic/ceramic Electrochemical Other separations: Water/CO_2 hydrates Integrated CO_2 separation with WGS			

SEQUESTRATION /STORAGE

Sequestration/Storage is defined as the placement of CO_2 into a repository in such a way that it will remain sequestered (or stored) for hundreds to thousands of years. Storage includes three distinct sub-areas: geologic sequestration, terrestrial sequestration, and ocean sequestration. Geological and terrestrial are near-term sequestration options. Ocean sequestration is not yet considered a viable sequestration approach due to the uncertainty regarding potential environmental impacts. Each of these sequestration areas is discussed below. Table 3 presents a synopsis of the CO_2 storage pathways and supporting research efforts.

GEOLOGIC SEQUESTRATION GOALS

2007 Conduct a CO_2 ECBM field test where coal permeability 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 Achieve CO_2 storage capacity prediction precision of ±30%.

Geologic Sequestration

Geologic sequestration is the storage of CO_2 in a range of underground geologic formations. The three primary types of formations, oil and gas reservoirs, unmineable coal seams, and saline formations, represent different challenges and opportunities for CO_2 storage as discussed below.

Oil and gas reservoirs. CO_2 can be injected into depleted oil and gas reservoirs and essentially replace the reservoir volume of the produced oil and/or gas. That such reservoirs have held crude oil and natural gas securely over geologic time frames bodes well for the permanence of CO_2 storage in them. Alternatively, CO_2 can be injected into a depleting oil reservoir, that is, a reservoir that is still producing oil but which is declining and nearing the end of production. Typically, primary oil recovery and secondary recovery via a water flood produce 30-40% of a reservoir's original oil in place (OOIP). Supercritical CO_2 is a strong hydrocarbon solvent that can be injected into a depleting reservoir to recover an additional 10-15% of the OOIP. A portion of the injected CO_2 remains in the reservoir, thus the link to sequestration. Historically, enhanced oil recovery (EOR) field operations have been focused on minimizing the amount of CO_2 that remains sequestered per barrel of oil recovered. The current industry average is 2,000 scf of CO_2 or less per barrel. A credit for CO_2 storage would shift the economics and alter field practices to optimizing CO_2 storage. Unfortunately not all depleted oil reservoirs are candidates for CO_2 EOR, nevertheless, numerous opportunities exist.

As a sequestration option, depleting oil reservoirs that are amenable to CO_2 EOR provide a value-added benefit in terms of revenues from enhanced oil production which can partially offset the cost of CO_2 capture. The CO_2 storage capacity of domestic oil and gas formations has been estimated at roughly 150 billion metric tons of $CO_{2,}$, roughly 30 years worth of U.S. emissions (Advanced Resources International, presentation at the meeting of the American Association of Petroleum Geologists, 2003). Depleting oil reservoirs cannot meet all potential greenhouse gas reduction needs, but they provide a good early opportunity at relatively low cost. R&D in this area is focusing on investigating the trapping mechanisms for CO_2 and developing reservoir management tools and strategies that simultaneously maximize CO_2 sequestration and oil recovery.

Unmineable coal seams. Unmineable coal seams are coal seams that are too deep or too thin to be mined economically. All coals have varying amounts of methane adsorbed onto pore surfaces, and wells can be drilled into unmineable coal beds to recover this "coal bed methane" (CBM). In fact, CBM is the fastest growing source of natural gas in the United States and accounted for 8 percent of domestic production in 2002. As with oil reservoirs the initial CBM recovery methods, dewatering and depressurization, leave a fair amount of the CBM in the reservoir. Additional CBM recovery can be achieved by sweeping the coalbed with nitrogen. CO_2 offers an alternative to nitrogen. It preferentially adsorbs onto the surface of the coal, releasing the methane. Two to three molecules of CO_2 are adsorbed for each molecule of methane released, thereby, providing an excellent storage sink for CO_2. The maximum domestic capacity for CO_2 ECBM has been estimated at 90 billion metric tons CO_2, 40 billion metric tons of which is in Alaska (Advanced Resources International, presentation at the meeting of the American Association of Petroleum Geologists, 2003). Like depleting oil reservoirs, unmineable coal beds are a good early opportunity for CO_2 storage.

Coal swelling is a potential barrier to CO_2 ECBM. It has been observed that when coal adsorbs CO_2, it swells in volume. In an underground formation swelling can cause a sharp drop in permeability, which not only restricts the flow of CO_2 into the formation but also impedes the recovery of displaced CBM. Laboratory tests and field studies have improved our understanding of coal swelling. Work is underway toward minimizing the negative effects of coal swelling on CO_2 ECBM.

Saline formations. Saline formations are layers of porous rock that are saturated with brine. The potential CO_2 storage capacity of domestic saline formations is enormous compared to oil reservoirs and coal beds and potentially represents centuries worth of CO_2 emissions storage. However, much less is known about saline formations than is known about crude oil reservoirs and coal seams.

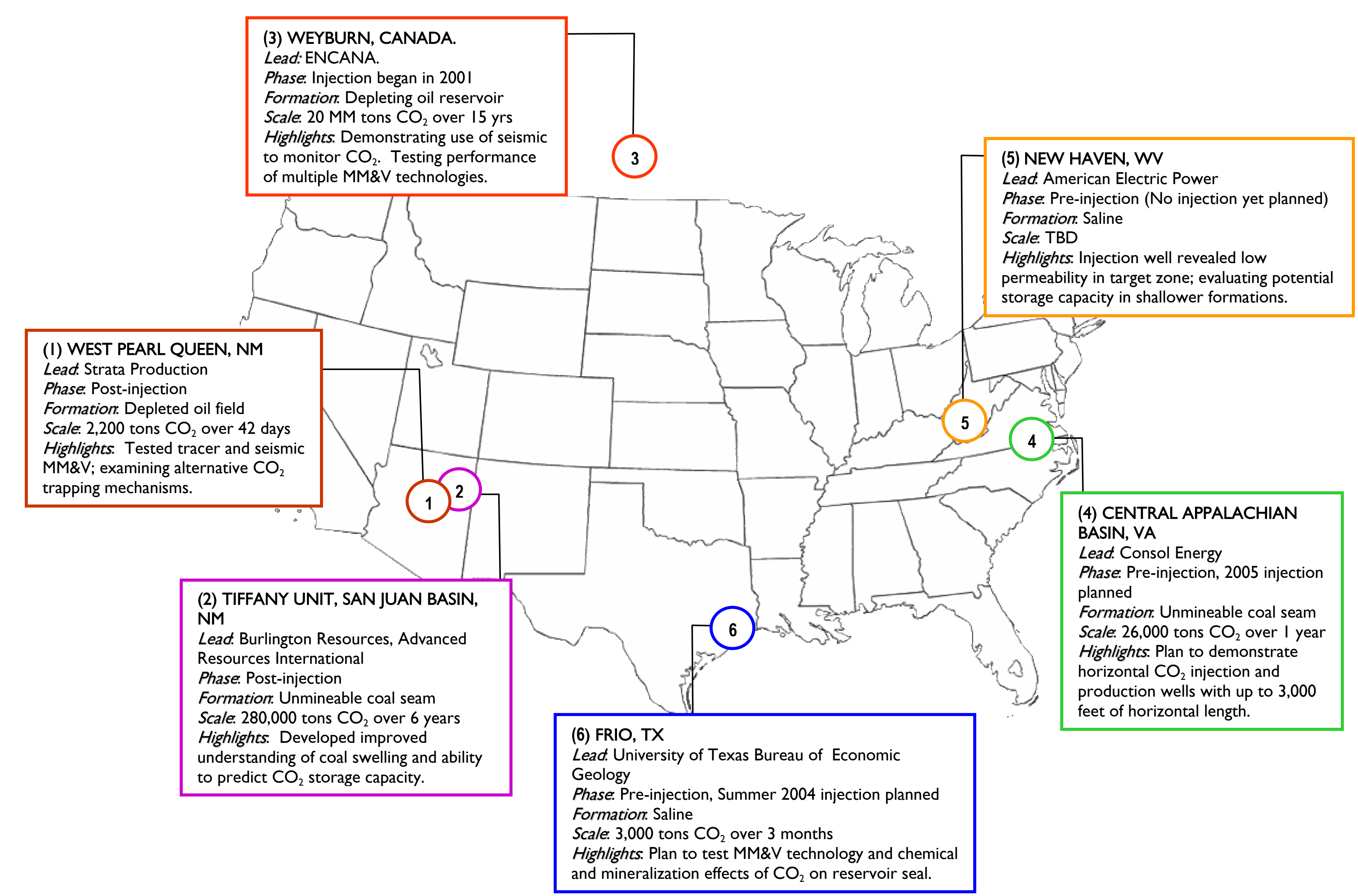
Many uncertainties and knowledge gaps exist for saline formations. R&D is directed toward the following: sequestration capacity; seal integrity; and reservoir properties such as faults, permeability and porosity. Saline formations also offer a unique characteristic in that they contain minerals that could react with injected CO_2 to form solid carbonates. These carbonate reaction mechanisms are being investigated as a potential pathway to ensure no CO_2 migration outside the reservoir and permanent storage. Carbonate formation can also potentially have negative effects by plugging the formation in the immediate vicinity of an injection well. R&D is seeking to understand all the factors and characteristics of saline formations and harness this information to enhance CO_2 injection and storage in these formations.

Field experiments are central to the program's geologic sequestration efforts. Figure 3 shows the robust portfolio of geologic sequestration field tests. The tests are in various phases of development and encompass depleted oil reservoirs, unmineable coal seams, and saline formations. Significant knowledge is being acquired with respect to identifying viable formation candidates; predicting CO_2 flow in a reservoir; estimating CO_2 storage capacity; and understanding CO_2 trapping mechanisms.

With the exception of the EOR project at Weyburn Oil Field in Canada and the Sleipner Gas Field in the North Sea, the field tests supported by the program are relatively small-scale (several thousand tons of CO_2, equivalent emissions to one days' worth from an average coal-fired power plant). Lessons learned from these small field tests will be applied to any future, larger-scale tests.

The program undertakes careful planning and preparatory work before CO_2 injection begins. The baseline reservoir condition is assessed, reservoir models are developed to predict behavior of injected CO_2, any necessary permits are obtained, infrastructure (e.g., injection wells, MM&V equipment, and CO_2 delivery) is established, and actions are taken to protect the environment. Each field tests has a strong modeling component, and serves as a venue for testing the capability of MM&V technologies and approaches. These models help us to understand what is happening during a field test and to correctly interpret data from MM&V equipment. With experience from field tests, the models will enable researchers to correlate measurable characteristics of a geologic formation to CO_2 storage capacity and permanence.

Figure 3. Geologic Sequestration Field Tests Supported by the Sequestration Program



Terrestrial Sequestration

Terrestrial sequestration is the enhancement of the uptake of CO_2 by plants that grow on land and in freshwater and, importantly, the enhancement of carbon storage in soils where it may remain more permanently stored. Terrestrial sequestration provides an opportunity for low-cost CO_2 emissions offsets. Early efforts include tree-plantings, no-till farming and other agricultural practices, and forest preservation. 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 activities in this area with the DOE Office of Science, U.S. Department of Agriculture, Environmental Protection Agency, and Department of Interior Office of Surface Mining. The scope of terrestrial sequestration options addressed in the core R&D Program is limited to the integration of energy production, conversion, and use with land reclamation. Specifically, this involves the reforestation and amendment of damaged soils, when possible, using solid residuals from coal combustion. Field demonstrations focus on improving the carbon storage of previously or abandoned mined land and optimizing land management practices. Current projects include a large-scale demonstration of reforesting recently mined lands in Virginia, West Virginia, and Kentucky and a smaller-scale demonstration integrating terrestrial sequestration with energy production by employing the use of coal combustion by-products. Together these projects will demonstrate effective sequestration on over 720 acres of previously mined land in Appalachia.

Ocean Sequestration

Compared to terrestrial ecosystems and geologic formations, the concept of ocean sequestration is in a much earlier stage of development. Ocean sequestration has huge potential as a carbon storage sink, but the scientific understanding to enable ocean sequestration to be considered as a real option is not yet available. A small level of funding is provided to leading researchers in this area to develop the necessary scientific understanding of the feasibility of ocean sequestration. Work is focused on understanding the mechanisms of CO_2 uptake in the ocean and assessing the environmental impacts of CO_2 storage. The Program is also funding laboratory experiments aimed at learning more about the basics of CO_2 behavior in an ocean environment and also the formation and behavior of CO_2 hydrates and collaborating with other Federal agencies.

Terrestrial Sequestration Goal

By 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.

Terrestrial Sequestration Field Tests

The Virginia Polytechnic Institute and State University and its corporate partners, Mead-Westvaco Corporation, Plum Creek Timber Company, and Pittston Coal Company, are working on restoring sustainable forests on mined lands in Virginia, West Virginia, and Ohio. They are classifying, mapping, and inventorying three 40-acre reclaimed strip mine sites in the southern Appalachians. Terrestrial sequestration testing will determine the biological and economic potential of reforesting these sites. Trees were planted in March 2004.

The University of Kentucky and project partners are studying terrestrial sequestration via low compaction surface mine reclamation techniques and the production of high value trees. Researchers are studying the effects of tree species and mixtures of species, as well as mine soil depth and type, on the rate of carbon sequestration. In 2003, over 150 acres were planted, with an additional 150 acres planned for 2004.

Table 3. Sequestration/Storage

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. Typical CO_2 storage rate is 2,000 scf of CO_2 per bbl oil recovered. With sustained favorable crude oil prices, interest in CO_2 EOR is high. Since 1998, CO_2 has been injected into a saline formation underlying the Sleipner natural gas production field in the North Sea at rate of one million tons CO_2 per year.	Depleting oil & gas reservoirs Unmineable coal seams Saline formations Depleting gas reservoirs Organically-rich shales	Capability to predict CO_2 storage capacity Enhanced CO_2 trapping Preservation of formation integrity, permeability	Five geologic sequestration field tests in various stages of development (see Figure 3). Preliminary results indicate significant CO_2 trapping at some EOR fields. Better understanding of coal swelling has been achieved. A CO_2 ECBM field test at Tiffany NM demonstrated recovery of 1 scf of CBM per 3 scf CO_2 sequestered.	2007 Conduct a CO_2 ECBM field test where coal permeability 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. There are tens of thousands of additional forests being studied to determine their potential to sequester CO_2. The United States has 1.5 million acres of land damaged by past mining practices.	Integration of terrestrial sequestration and fossil-based energy systems Soil reclamation using CCBs or other solid residuals Tree plantings to offset greenhouse gas emissions Optimizing silvicultural practices for degraded lands.	Enhanced carbon transfer from plant to soil	Field projects will demonstrate effective sequestration on over 720 acres of previously mined land in Appalachia, which includes Kentucky, Virginia, and West Virginia.	2007, develop optimization strategies and best practice guidelines for maximizing carbon sequestration potential on unproductive mine lands. By 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	High pressure, low-temperature water tank used to demonstrate effect of phases on hydrate buoyancy. Monterey Bay Aquarium continues investigating all aspects of CO_2 hydrate formation near ocean floor.	Improved scientific understanding of this option.

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 way that is permanent and not harmful to the host ecosystem. The title and scope of this area has been revised to include "mitigation." 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. Above-ground 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. Table 4 presents the roadmap for MM&V, including R&D highlights from the research portfolio.

MM&V Goals

By 2006 develop instrumentation and measurement protocols for direct sequestration in geologic formations and for indirect sequestration in forests and soils that enable the implementation of wide scale emissions accounting and trading schemes.

By 2010 develop instrumentation and protocols to accurately measure, monitor, and verify both carbon storage and the protection of human and ecosystem health for carbon sequestration in terrestrial ecosystems and geologic reservoirs. MM&V systems should represent no more that 10% of the total sequestration system cost.

Using Aerial Photographs to Measure Carbon Sequestration in Forests

Working with the Nature Conservancy and a team of technology developers, DOE is funding the development of Multi-Spectral 3-Dimensional Aerial Digital Imagery (M3DADI) for terrestrial sequestration MM&V. Dual cameras and laser attached to an airplane create a three-dimensional image of a forest plot. From correlations, these modeled images are used to estimate the amount of carbon sequestered. Subsequent flyovers can be used to detect small changes and help operators identify trouble spots. The technology has been demonstrated and is now being verified in several large forestation projects by comparison to conventional sampling methods.

Table 4. Monitoring, Mitigation, and Verification

Technology Roadmap			Supporting Program Activities	
Current State of the Art	**Priority Research Pathways**	**Cross Cut Pathways**	**R&D Highlights**	**Program Goals** *Enable sequestration. to provide emissions reduction credit*
Soils MM&V Current on-the-ground measurements are accurate within 5-30% and can cost as little as $3 per CO_2 offset.	Laser induced breakdown spectroscopy (LIBS) Inelastic Neutron Scattering Soil Carbon Analyzer	CO_2/carbon fate and transport models Protocols for using advanced MM&V technologies in commercial systems Risk analysis protocols	Complete construction and testing of person portable LIBS Complete calibrations of scanning system	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 An MM&V protocol enables 95% of CO_2 injected into a geologic reservoir to be credited and represents no more than 10% of the total sequestration cost.
Subsurface MM&V 3D seismic can detect CO_2 with a resolution of 4 meters thickness.	Monitoring and Detection Devices Surface to borehole seismic Micro-seismic Cross well electromagnetic Electrical resistance tomography CO_2 tracers Surface leak detection Modeling Mineralization Concepts for Leakage Mitigation		Completed Phase I MM&V activities for Weyburn EOR project Completed tracer test activities at West Pearl Queen field in New Mexico Completed preliminary MM&V strategy for CO_2 injection project in the Frio Saline Formation Completed a micro-gravimetric survey of Sleipner Utsira saline formation	
Above-Ground MM&V Traditional field practices provide fairly accurate estimates of above-ground carbon, but these methods are time consuming and labor intensive. New technologies are needed to evaluate terrestrial storage on regional scales.	Multi-Spectral 3-Dimensional Aerial Digital Imagery (M3DADI)		Completed flyovers of the Delta National Forest in Mississippi to measure carbon storage	

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.

During the past year, the Sequestration Program continued a partnership with the National Research Council (NRC)/ National Academy of Sciences (NAS) to bolster R&D efforts in Breakthrough Concepts. A workshop hosted by DOE and NRC produced the following four priority areas:

- Advanced sequestration techniques
- Advanced subsurface technologies
- Advanced geochemical methods for sequestering carbon
- Novel niches

The collaboration with the NRC/NAS was a big success; a solicitation produced over one hundred proposals. A committee from NRC/NAS reviewed the pool of proposals and provided DOE with a screening assessment. DOE closely evaluated the proposals and awarded contracts in March 2004 to the seven projects described in Table 5.

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. The challenge is to identify an oxygen transfer material with a combination of desirable chemical and physical properties. Alstom Power and other private sector firms are researching chemical looping concepts.

Table 5. Recently-Awarded Breakthrough Concepts Research Project

Area	Title	Description
Advanced CO_2 Capture	Hydrogen Selective Silica Membrane	Develop a new method for making extremely thin, high-temperature, hydrogen-selective silica membranes [University of Minnesota]
	Dual Function Membrane	Develop a membrane that will use both pore structure and an amine chemical adhered to the membrane to achieve higher CO_2 selectivity than is possible using pore size alone. [University of New Mexico, T3 Scientific]
	Ionic Liquids	Conduct basic research into the use of ionic liquids (organic salts that are liquid at room temperature and exhibit unusual properties) for CO_2 capture. [University of Notre Dame]
	Microporous Metal Organic Frameworks (MOFs)	Search for novel microporous metal organic frameworks (MOFs) suitable for CO_2 capture. MOFs are hybrid organic/inorganic structures at the nano scale to which CO_2 will stick. [UOP LLC, University of Michigan, Northwestern University]
Advanced Subsurface Technologies	Carbonate Sediments Below the Sea Floor	Using laboratory-scale simulations, study the potential of calcium carbonate sediments to absorb injected CO_2 at the elevated pressures and temperatures found in subsea formations. [Harvard University, Columbia University, Carnegie-Mellon University, University of California at Santa Cruz]
	Mineral Carbonation	Study the chemistry and kinetics of the CO_2 carbonation reaction in olivine and other commonly occurring minerals. Investigate the use of sonic frequencies and other methods to enhance the reaction. [Arizona State University]
Novel Niches	Microbial CO_2 Conversion	Create strains of microbes that feed off CO_2 and produce salable by-products, such as succinic, malic, and fumeric acids. [University of Georgia]

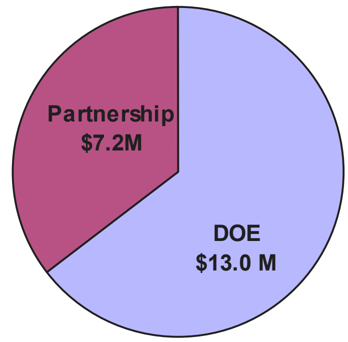
NON-CO_2 GREENHOUSE GAS CONTROL

Because non-CO_2 greenhouse gases (e.g., methane, N_2O, and high global warming potential gases) can have 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. Three projects are currently being funded: 1) minemouth ventilation methane mitigation [http://www.netl.doe.gov/publications/factsheets/project/Proj248.pdf] 2) impermeable membranes for landfill gas recovery [http://www.netl.doe.gov/publications/factsheets/project/Proj199.pdf], and 3) separating the nitrogen methane streams to enable more methane recovery from landfills and coal mines [http://www.netl.doe.gov/publications/factsheets/project/Proj253.pdf]. The Sequestration Program is also working with the United States Environmental Protection Agency (EPA) to assess the role that non-CO_2 greenhouse gas emissions abatement actions can play in a nationwide strategy for reducing greenhouse gas emissions intensity. The EPA and DOE are working jointly to identify priority areas for research and development.

B. Regional Partnerships

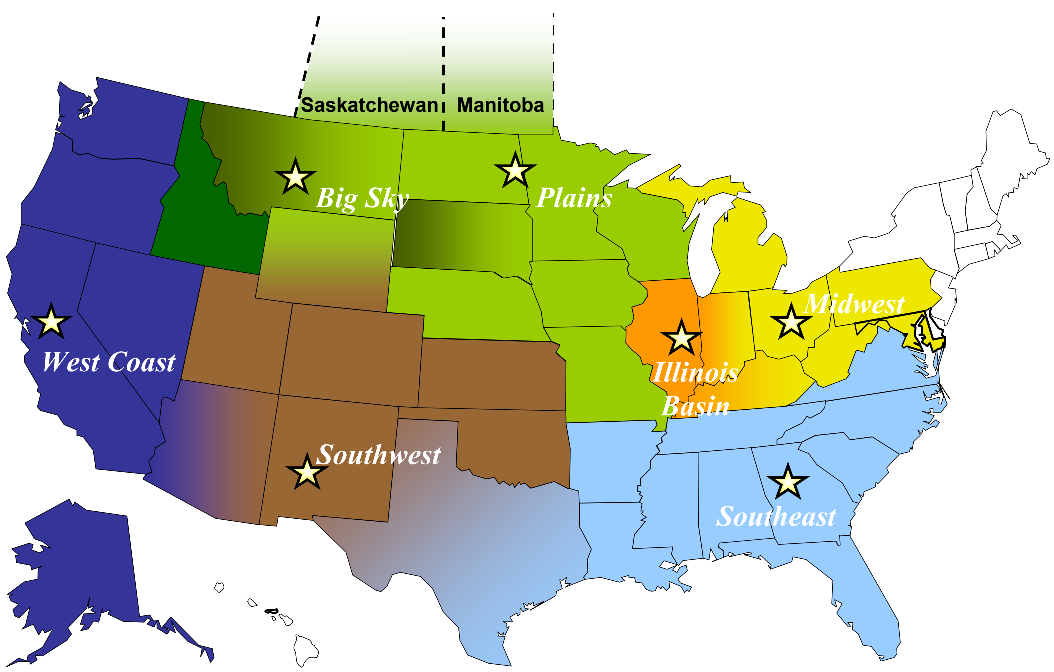
In 2003, the DOE awarded seven regional carbon sequestration partnerships. These partnerships are teams comprised of state agencies, universities, and private companies with the goal of evaluating and pursuing opportunities for carbon sequestration deployment. Each partnership is focused on a specific region of the country, and its efforts pertain to the local ecosystem, the local geology, and the types of CO_2 emissions sources and sinks found in the region. Together the seven partnerships will form a network of capability, knowledge, and infrastructure to enable carbon sequestration technology to play a major role, if needed, in a national strategy to mitigate GHG emissions.

The Partnerships Achieved an Average Cost-Share of 36%



The seven partnerships were awarded after a vigorous competitive process. The competition motivated the awardees to assemble robust teams and to offer an average 39 percent cost share. The partnerships will be conducted as a two phase process. The first phase, which is ongoing in 2003 and 2004, is a planning stage. During that stage, sources and potential sinks will be identified and assessed. Regulatory and performance requirements for future deployments will be determined. Action plans will then be developed leading to the validation of all sequestration concepts investigated by the partnerships. After the Phase I activities are completed, a Phase II solicitation will be issued. Phase II will focus on implementing regional action plans and validating all concepts in the field, as appropriate. Phase II is still in the planning stages and any details at this stage are subject to change. It is estimated that each Phase II project would be funded in the range of \$3,000,000 to \$5,000,000 per year. Phase II is anticipated to be an eight year initiative and the

Figure 4. Regional Carbon Sequestration Partnerships



number of potential Phase II projects will be dictated by future programmatic budget constraints. It is expected that the regional carbon sequestration partnerships will become self-sustaining after Phase II, should a carbon constrained scenario be necessary.

Each regional partnership will produce the following four discreet products during Phase I. Note that though the framework is consistent, each partnership has tailored its efforts to suit the opportunities for sequestration within its region.

A National Sequestration Network

The Program is working to foster coordination and information sharing among the Regional Sequestration Partnerships. As a start, representatives from all seven partnerships attended a kick-off meeting held on November 9, 2003, and presented their plans and initial findings.

Up-to-date information concerning the partnerships, as well as links to individual partnerships web pages, can be found on the NETL website at: http://www.netl.doe.gov/coalpower/sequestration/partnerships/

1. Regional Carbon Sequestration Atlases

These atlases will show all the point sources of CO_2 emissions in a region, overlain on the geologic formations that have potential for CO_2 storage. The CO_2 point sources will be characterized according to volume, CO_2 concentration, contaminants, pressure, and other criteria so that its suitability for CO_2 capture may be assessed. Similarly, geologic formations will be characterized according to type, estimated CO_2 storage capacity, as well as potential for value-added by-products associated with CO_2 storage (e.g., enhanced oil recovery and enhanced coal bed methane recovery). The objective of the atlases is to clarify which CO_2 emissions sources are amenable to capture and located near potentially favorable geologic repositories. The atlases will also document and characterize opportunities for terrestrial sequestration. Regional atlases will optimize source and sink locations, otherwise, the pipeline infrastructure for sequestration could prove cost prohibitive.

2. Regional Project Implementation Plans

Each partnership will identify the most promising sequestration projects in its region. The priority projects can be either terrestrial and/or geologic sequestration. Each partnership will craft a rationale for the project selections and perform cost/benefits analyses. The partnership will develop a project-level plan for regulatory compliance and public outreach and education, and will identify MM&V requirements for each project. These priority projects will serve as the basis of each partnership's field validation proposal.

3. Action Plan for Regulatory Compliance

These plans will identify the national and local environmental regulations that may impact future sequestration deployments in each partnership region. Each partnership will identify the areas of increased understanding, sequestration technology performance metrics, MM&V capability, and risk assessment requirements needed to address and comply with environmental regulations. The partnerships will also address liability aspects to sequestration and proposed plans to handle these issues. The partnerships' action plans will identify expected timelines for regulatory permitting, reporting requirements, and parties that are responsible for various requirements associated with projects in that region.

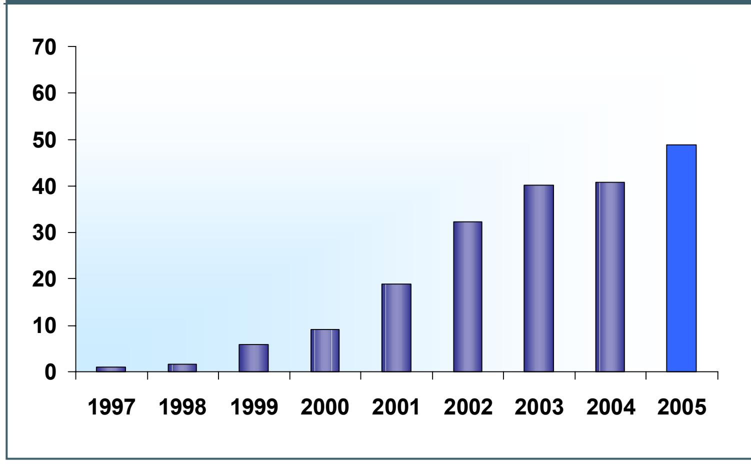
4. Action Plan for Public Outreach and Education

Engaging people in the regions is a critically important role for each of the partnerships. Each partnership will produce a plan that sets forth methods for public engagement and tools for stakeholder education. The plans will also note any regulatory requirements for public outreach.

C. Program Management

The DOE is dedicated to achieving the Sequestration Program goals and to utilizing the Program funds 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 5. Carbon Sequestration Program Budget ($million)



Public/Private Partnerships

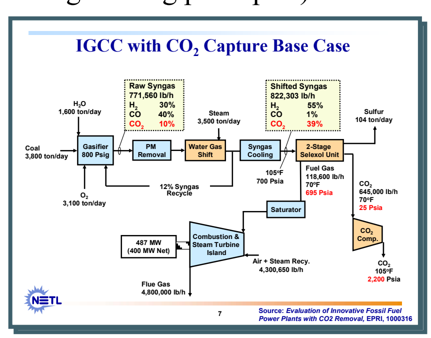
Public-private partnerships and cost-shared R&D are a critical part of technology development for carbon sequestration. These relationships draw on pertinent capabilities that the oil and gas, coal, electricity supply, refining, and chemical industries have built up over decades and a technical knowledge base shared with the national laboratories, federal and state geological surveys, and academia. The program prefers to engage 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. 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. About one-fourth of the Carbon Sequestration Program funding is allocated to university-led research efforts.

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 NETL with a scientific understanding of the underlying technologies and, thus, enhances its effectiveness in implementing the carbon sequestration R&D portfolio.

Systems Analyses

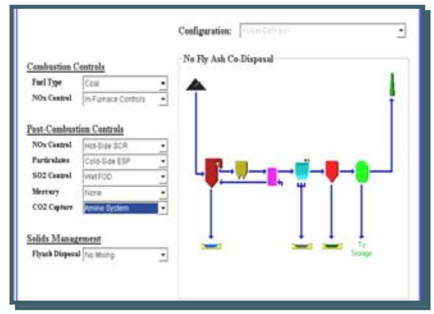
Systems analyses and economic modeling of potential new processes are crucial to providing sound guidance to R&D efforts, which are investigating a wide range of CO_2 capture options. The project evaluation effort includes two interrelated areas. First is the conceptual scale-up (using sound engineering principles) of novel CO_2 capture technologies from bench/pilot scale to commercial scale. Second is the development of computer models to evaluate the performance and economics of these conceptual designs. Ongoing systems analyses are performed on NETL in-house R&D (CSSFA) CO_2 capture technologies, as well as processes being developed through our Core R&D projects and outside the Program. Since the majority of new CO_2 capture technologies are still at a bench scale level of development, a scaled up conceptual design is first generated with emphasis on mass and energy balances. Based on available data and/or engineering estimates, each system is optimized, and "what-if" scenarios are



evaluated to identify barriers to deployment and help the process developers establish system performance targets. The current portfolio of systems analyses includes both pre- and post-combustion CO_2 capture technologies, such as wet scrubbing (advanced amines, aqueous ammonia), solid regenerable sorbents (pressure swing and temperature swing regeneration), and membrane-based separations.

Modeling

A comprehensive economic model is needed that will enable different options for CO_2 capture to be systematically evaluated, including pipeline and geologic storage costs. Carnegie Mellon University has developed a model, called the Integrated Environmental Control Model-Carbon Sequestration (IECM-CS). The focus of this model is current commercial technologies, such as amine-based CO_2 capture, Selexol-based CO_2 capture, shift conversion, pipeline transport, and geologic storage. The model is capable of establishing a common set of performance metrics and evaluating the overall cost of CO_2 sequestration. To complement the CMU model, NETL and Science Applications International Corporation are developing a computer model based technique for evaluating new and developing CO_2 capture and sequestration technologies. Technologies that have been modeled range from ideas at a conceptual stage to processes evaluated at an advanced pilot scale. With existing studies as a starting point, other technologies in the portfolio will be evaluated to continually assess their potential technical and economic merit.



Coordination with other Domestic RD&D Activities

The Program cooperates and collaborates with relevant domestic RD&D efforts. For example, the Program's longer-term research efforts are coordinated with DOE's Office of Science, the National Science Foundation, and within the academic research community. In geologic sequestration, the program is collaborating with RMOTC and in terrestrial sequestration, collaborative opportunities are being pursued with the United States Department of Agriculture and Department of the Interior.

International Collaboration

On February 27, 2003, President Bush directed Secretary of Energy Spencer Abraham and Under Secretary of State for Global Affairs Paula Dobriansky to initiate the formation of the Carbon Sequestration Leadership Forum (CSLF), an international climate change initiative that will focus on development of carbon capture and storage technologies as a means to accomplishing long-term stabilization of greenhouse gas levels in the atmosphere. Scientific and technological information gathered from participating countries will be aggregated, summarized, and distributed to all of the Forum's participants. Joint projects will be identified by member nations with the Forum serving as a mechanism for bringing together government and private sector representatives from member countries.

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. The International Energy Agency's Greenhouse Gas Research and Development Programme (IEA/GHG),

Carbon Sequestration Leadership Forum Partners

Australia
Brazil
Canada
China
Colombia
European Commission
Germany
India
Italy
Japan
Mexico
Norway
Russian Federation
South Africa
United Kingdom
United States

which is funded by 18 members, including the European Union, Australia, Canada, Italy, Japan, Norway, and eight private sector sponsors, is one venue for collaboration.

The Program is also engaged with international entities through its participation in the CO_2 capture project (CCP). The CCP is a consortium of eight major energy companies, the European Union, and Norway. The Program has supported consortium research in the areas of CO_2 capture and geologic sequestration. Through participation in the CCP, the Program has been able to significantly leverage its funds and also develop a relationship with highly capable partners.

Global Climate Change Curriculum

Recognizing the complexity of the Global Climate Change issue and the need to improve understanding of it 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. The curriculum consists of a detailed set of lesson plans, teaching tools, activity and experiment descriptions and background materials. A test group of teachers will be trained with the curriculum and implement it during the 2004-2005 school year.

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

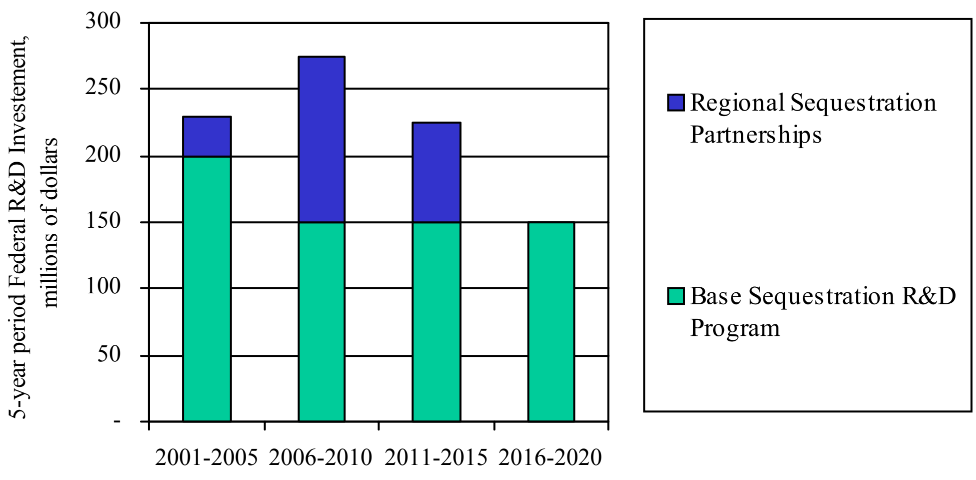
In addition the program management team participates in technical conferences through presentations, panel discussions, breakout groups, and other formal and informal venues. These efforts expose professionals working in other fields to the technology challenges of sequestration and also enable examination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

As with any new technology, there are environmental issues associated with carbon sequestration that need to be explored, understood, and addressed. The level of uncertainty is higher for some sequestration options than for others. A significant portion of the Program's R&D portfolio is aimed at an improved understanding of potential environmental impacts. In concert with R&D, the Program seeks to engage NGO's and federal, state, and local environmental regulators to raise awareness of what the Program is doing in this area, and the priority it places on systems that preserve human and ecosystem health. Some of the Program's R&D projects have their own outreach component. For example, the cost-shared project with the Nature Conservancy on monitoring, mitigation, and verification in terrestrial ecosystems has helped the program to engage non-governmental organizations and the environmental community. Also, the Regional Partnerships will enhance technology development but also engage regulators, policy makers, and interested citizens at the state and local level. 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.

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, 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." 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.

Resource Requirements
Figure 5 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, with slightly more between 2006 and 2010. The Regional Partnerships require an initial investment but are structured to become self-sustaining by 2013.

Figure 5. 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:

SCOTT KLARA
National Energy Technology Laboratory
Office of Coal and Power Systems
Office of Fossil Energy
(412) 386-4864
Scott.Klara@netl.doe.gov

SARAH FORBES
National Energy Technology Laboratory
Office of Coal and Power Systems
Office of Fossil Energy
(304) 285-4670
Sarah.Forbes@netl.doe.gov

LOWELL MILLER
Office of Coal and Power Systems
Office of Fossil Energy
(301) 903-9451
Lowell.Miller@hq.doe.gov

BOB KANE
Office of Coal and Power Systems
Office of Fossil Energy
(202) 586-4753
Robert.Kane@hq.doe.gov

JAY BRAITSCH
Office of Coal and Power Systems
Office of Fossil Energy
(202) 586-9682
Jay.Braitsch@hq.doe.gov

or visit our web sites at:

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

NATIONAL ENERGY TECHNOLOGY LABORATORY

626 Cochrans Mill Road
P.O. Box 10904
Pittsburgh, PA 15236-0940

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

National Energy Technology Laboratory

626 Cochrans Mill Road
P.O. Box 10904
Pittsburgh, PA 15236-0940

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

Customer Service: 1-800-553-7681
Website: www.netl.doe.gov

Printed in the United States on recycled paper

April 2004