United States Department of Energy • Office of Fossil Energy • National Energy Technology Laboratory

Carbon Sequestration

Technology Roadmap and Program Plan 2005

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

May 2005

A Message to our Stakeholders

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

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

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

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

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

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

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

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

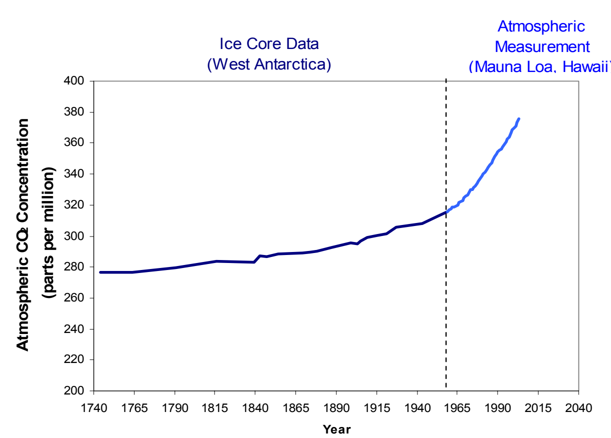
This document provides a vision of how to proceed with the development of carbon sequestration technology and is itself an important medium for engaging stakeholders. We invite readers to examine this document carefully and provide feedback to the contact persons listed on the back cover. Through a cooperative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

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

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

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

Figure 1. Atmospheric CO_2



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

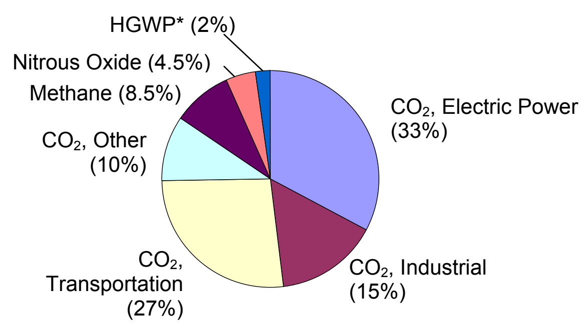
Elevated amounts of atmospheric CO_2 have two primary effects that are of concern to scientists. First, CO_2 in the atmosphere exerts a greenhouse effect that traps solar energy within the earth's ecosystem. An increased amount of greenhouse gases in the atmosphere may warm the planet overall and could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

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

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

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

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



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

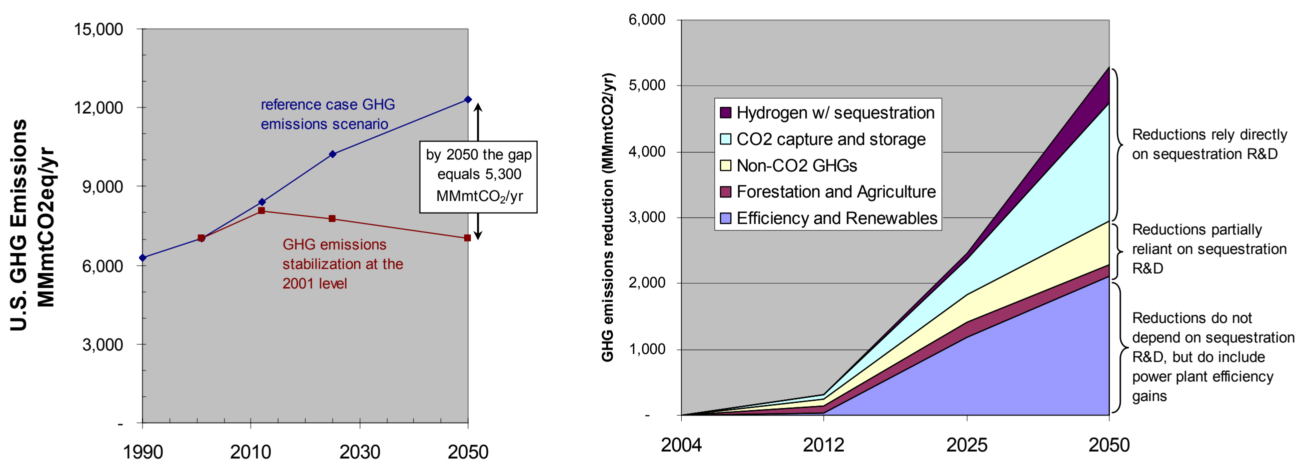
Source: DOE Energy Information Administration
Total 2003 U.S. GHG emissions were 6,891 million metrics tons CO_2 equivalent.
Methane, Nitrous oxide, and HGWPs reported in 100 year forcing CO_2 equivalents
** High global warming potential gases, e.g., certain refrigerants.*

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

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

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

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



Chapter 2. Carbon Sequestration Technology Roadmap and Program Plan

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

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.

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

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

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

Table 1. Top-level Carbon Sequestration Roadmap

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

A. Core R&D

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

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

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

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

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

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

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

Table 2. CO_2 Capture Roadmap

<table>
<tr><th colspan="3">Technology Roadmap</th><th>Program Goals</th></tr>
<tr><th>CO₂ Capture Applications</th><th>Priority Research Pathways</th><th>Cross Cut Pathways</th><th>Reduce cost and parasitic load</th></tr>
<tr><td>Post-Combustion CO_2 capture</td><td>Chemical sorbents</td><td rowspan="3">Heat integration
Improved base process efficiency
Oxygen separation technology
Gas/liquid contacting
Integration of CO_2 capture with NO_x/SO_x/Hg/PM control</td><td rowspan="3">2004 Pilot-scale demo of 75% reduction in CO_2 recycle requirements. *GOAL MET

2007 Develop at least two capture technologies that each result in less than a 20% increase in cost of energy services.

2012 Develop at least four capture technologies that each result in less than a 10% increase in cost of energy services</td></tr>
<tr><td>Pre-Combustion CO_2 capture</td><td>Chemical sorbents
Physical sorbents
Membranes
Water/CO_2 hydrates</td></tr>
<tr><td>Oxyfuels</td><td>Oxygen/recycle flue gas boilers
Chemical looping</td></tr>
</table>

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

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

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

Table 3. Technology-specific Breakdown of CO_2 Capture Options

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

Table 4. CO_2 Capture Research Projects in Program Portfolio

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

* Carbon Sequestration Science Focus Area (CSSFA)

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

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

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

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

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

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

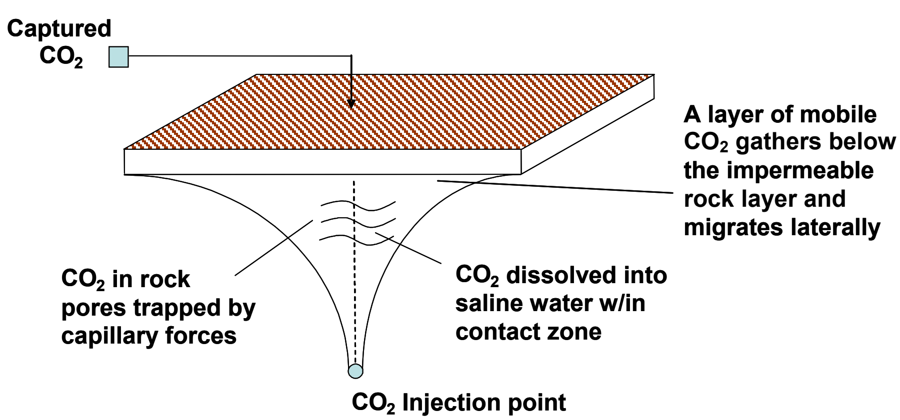
Table 5. Carbon Storage Roadmap

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

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

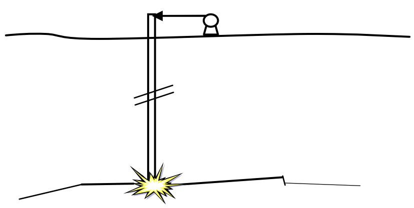
1. Capillary trapping. The surface of sandstone and other rocks preferentially adheres to saline water over CO_2. If there is enough saline water within a pore (75-90% of the pore volume), it will form a capillary plug that traps the residual CO_2 within the pore space.
2. Dissolution in saline water.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

Figure 4. CO_2 Storage Mechanisms

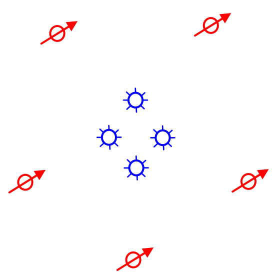


These advanced trapping mechanisms are only effective to the degree CO_2 comes into contact with the rock or coal within a formation. New injection techniques are being developed to maximize CO_2 contact within the reservoir. For example, accurate reservoir characterization can reveal the location of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

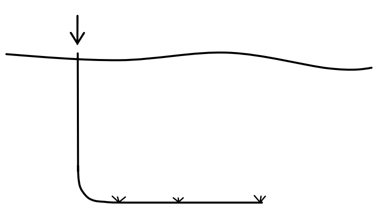
Figure 5. Examples of Advanced Drilling and CO_2 Injection Techniques



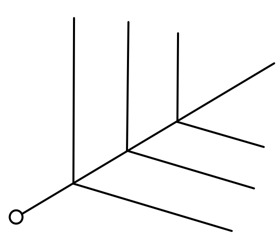
Hydrostatic pressure applied to a conventional vertical well can be used to engineer fractures in the rock that enable greater horizontal distribution of injected CO_2.



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



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



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

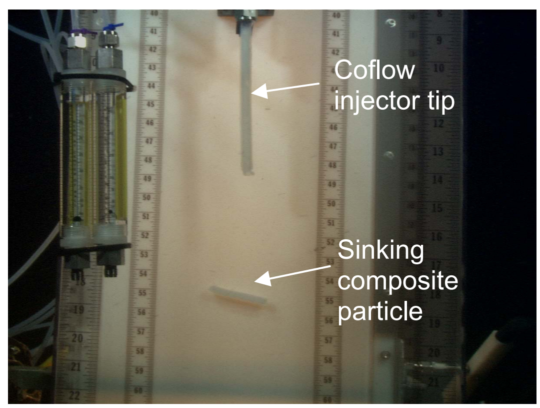
Terrestrial sequestration. Terrestrial sequestration is the enhancement of CO_2 uptake by plants that grow on land and in freshwater, and carbon storage in soils. Tree-plantings, no-till farming, forest preservation and other early activities provide an opportunity for low-cost CO_2 emissions offsets.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

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

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

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

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



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

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

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

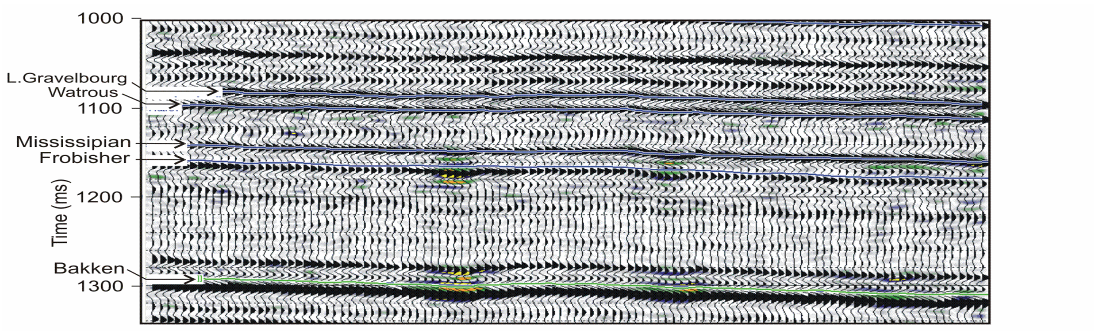
Modeling. Modeling is the understanding of the forces that influence the behavior of CO_2 in a reservoir, and the simulation of that understanding in a computer program that enables one to predict the fate and transport of injected CO_2. Modeling is important due to the very fundamental fact that a geosequestration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

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

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

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

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



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

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

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

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

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

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

Table 6. MM&V Roadmap

Technology Roadmap			Supporting Program Activities	
Pathways		Cross-cut Pathways	Research Highlights	Goals
Geologic Formations	Modeling Reservoir models (CO_2 flow from target to vadose) Geochemical models Geomechanical models Plume tracking Surface to borehole seismic Micro-seismic Cross well tomography Reservoir pressure monitoring Observation wells/fluid sampling CO_2 leak detection Vadose zone soil/water sampling Air sample/gas chromospectrometry Infrared-based CO_2 in air detectors Vegetation growth rates CO_2 tracers, natural and introduced Well testing Sub-surface monitoring wells Mitigation De-pressure target formation Pressure, permeability plug Interception, pump and treat	Integrated flow, geochemical, and geomechanical models Ecosystem response models Model use to focus monitoring on higher-risk leakage areas Risk analysis protocols Protocols for using advanced MM&V technologies in commercial systems	3D seismic tests conducted at the Weyburn field show the ability to detect volumes of CO_2 within the geologic formation as small as 2,500 metric tons. Completed a rigorous flow model of CO_2 injection into the Frio Saline Formation. Completed a micro-gravimetric survey of Sleipner Utsira saline formation.	2006 Apply promising MM&V technologies to at least several sequestration field tests or commercial applications. 2008 An MM&V protocol enables 95% of CO_2 uptake in a terrestrial ecosystem to be credited and represents no more than 10% of the total sequestration cost. 2012 CO_2 material balance greater than 99%. 2012 An MM&V protocol enables 95% of CO_2 injected into a geologic reservoir to be credited.
Terrestrial Ecosystems	Modeling Above/below ground correlations Cash flow models of terrestrial sequestration Plant matter measurement Multi-spectral 3-dimensional ariel digital imagery Satellite imagery Light Detection and Ranging (LIDAR) Soil carbon measurement Laser-induced breakdown spectroscopy (LIBS) Inelastic Neutron Scattering Soil Carbon Analyzer		Completed flyovers of the Delta National Forest in Mississippi to measure carbon storage. Complete construction and testing of person portable LIBS. Complete calibrations of scanning system.	

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

Table 7. Non-CO_2 GHG Roadmap

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

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

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

Chemical Looping

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

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

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

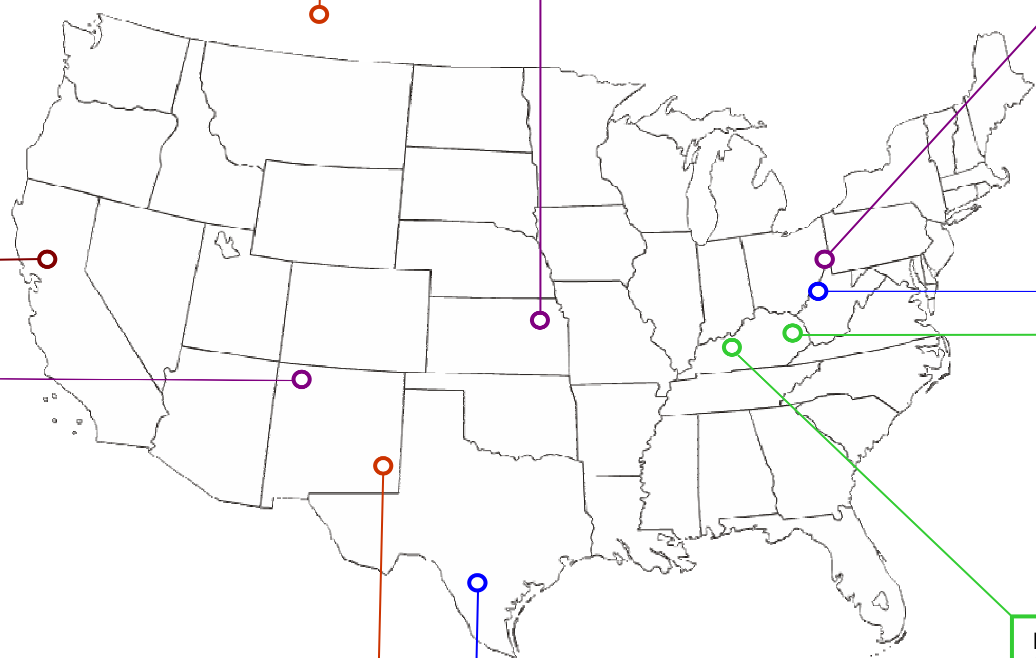
Figure 8. Carbon Sequestration Field Projects

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

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

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

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



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

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

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

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

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

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

B. Infrastructure Development

Regional Partnerships

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

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

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

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

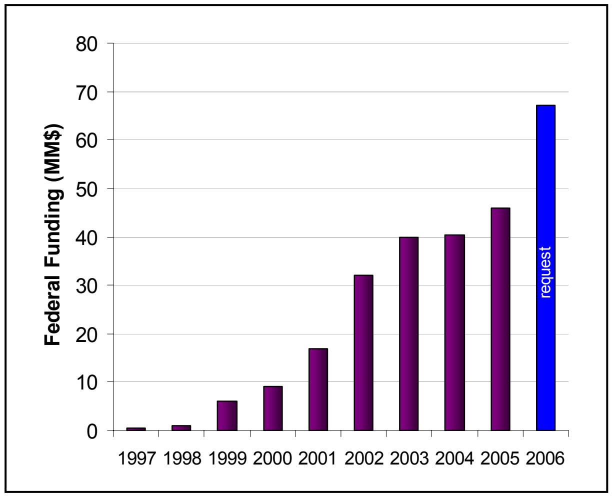
In FY 2009 DOE will consider an optional Phase III effort for the RCSPs. The third phase, which would run through 2013, is contingent upon continued importance/synergies to the FutureGen initiative, the need for the validation of additional sequestration sites throughout the United States, and budget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

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

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

C. Program Management

Figure 9. DOE Sequestration Program Budget



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

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

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

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

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

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

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

Charter CSLF Signing Ceremony, June 2003

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

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

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

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

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

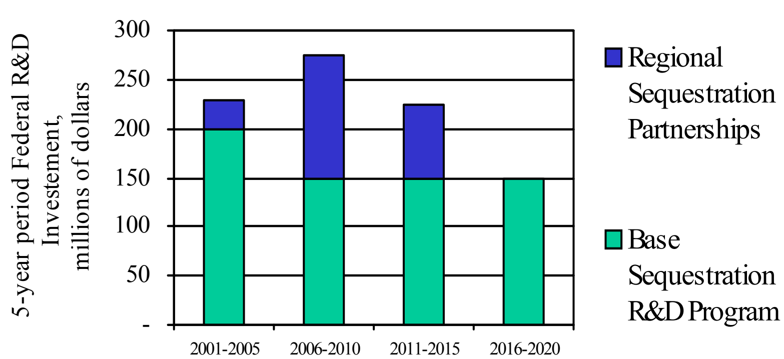
- Carbon Sequestration Webpage at the NETL site
- Monthly sequestration newsletter
- The Sequestration Technology Roadmap and Program Plan, revised annually
- The National Conference on Carbon Sequestration, held annually in the late spring in the Washington, DC, area
- Educational curriculum on global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

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

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

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

Figure 10. Funding Requirements of the Carbon Sequestration Program



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

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

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