A Message to Our Stakeholders

The availability of clean, affordable energy is essential for the prosperity and security of the United States and the world in the 21st century. About 85 percent of U.S. energy is derived from fossil fuels, and continued reliance on these fuels is forecast well into the 21st century. At the same time, increased concentrations of carbon dioxide (CO_2) due to carbon emissions are expected unless energy systems reduce the carbon load to the atmosphere. Accordingly, carbon sequestration — carbon capture, separation, and storage or reuse — must play a major role if we are to continue to enjoy the economic and energy security benefits which fossil fuels bring to our Nation's energy mix.

The requirements for carbon sequestration are challenging. The technologies and practices to sequester carbon must 1) be effective and cost-competitive, 2) provide stable, long-term storage, and 3) be environmentally benign. Carbon sequestration is in a very early stage of scientific and technical understanding. Much work remains to be done to understand the science and to assess the technology options and their potential in meeting the challenge.

This document is the draft Program Plan for the Carbon Sequestration Program. It describes the program drivers and goals, the R&D portfolio, program strategy, and program benefits. The plan is the direct result of collaborative work with our stakeholders. To date, key interactions include:

- The Stakeholder's Workshop on Carbon Sequestration for DOE, hosted by the Massachusetts Institute of Technology (MIT) in June 1998
- The joint Office of Fossil Energy and Office of Science report *Carbon Sequestration: State of the Science*, April 1999
- Ongoing outreach and discussions with industry, university, and government stakeholders.

In FY 1999, to obtain further stakeholder input on the needs, opportunities, and priorities for carbon sequestration, program outreach activities include:

- A FETC and EPRI jointly sponsored workshop with the electric generation industry
- Follow-up workshops on the evolving science and technology needs to define a technology roadmap
- A jointly sponsored industry / DOE / International Energy Agency (IEA) workshop on geologic storage
- Joint sponsorship of other workshops with the IEA Greenhouse Gas Programme.

Only with your involvement and support can we succeed. Our goals are challenging. A cooperative partnership of industry, academia, and government will have the best chance of succeeding. We welcome your comments and suggestions about the plan. Please respond directly to us or to the contacts listed on the back cover.

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Carbon Sequestration
R&D Program Plan: FY 1999 - FY 2000

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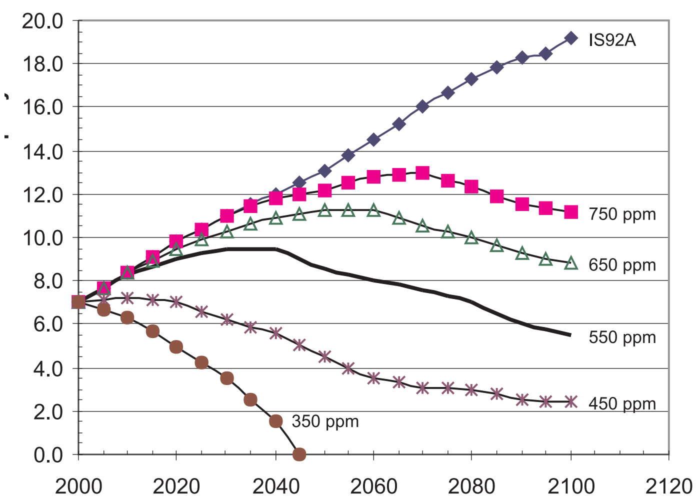
The World Tomorrow

The concentration of carbon dioxide (CO_2) in the atmosphere is rising and, due to growing concern about its effects, the United States and 160 other countries ratified the Rio Mandate, which calls for "... stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."

While the level of greenhouse gases that represents "stabilization" is open to debate, a range of 350-750 parts per million (ppm) is widely discussed, as shown in the various scenarios represented in Figure 1. Compared to the reference no-stabilization scenario (IS92A in Figure 1), even modest stabilization will require enormous amounts of fossil energy with very low greenhouse gas emissions. Many government, industry, and academic organizations are now recognizing the major role that carbon sequestration must play if we are to continue to enjoy the economic and energy security benefits which fossil fuels bring to our Nation's energy mix. Accordingly, the Department of Energy's Office of Fossil Energy is developing a collaborative R&D program on carbon sequestration.



Source: *Nature*, Volume 379, January 18, 1996, pp. 240-243

Figure 1. Scenarios for the Stabilization of Global Carbon

The Technical and Market Challenge

Under virtually any stabilization and market scenario, fossil fuels will remain the mainstay of energy production for the foreseeable future. To achieve any level of atmospheric stabilization that is ultimately deemed acceptable, there are three basic options: (1) reduce the carbon content of fuels, (2) improve the efficiency of energy use, and (3) capture and sequester the carbon. The Office of Fossil Energy's Vision 21 program directly addresses the first two: the need for decarbonized fuels such as hydrogen (H_2) and the need for improvements in efficiency.

These two measures are only part of the answer. Option (3), large-scale, low-cost sequestration of carbon, also will be required — a need for which no cost-effective technology exists today. Moreover, this technology will be needed not just for new capacity for energy growth, but to replace existing capacity in capital-stock turnover. The Vision 21 and carbon sequestration portfolios will jointly address the need for effective technology for atmospheric stabilization. This document focuses on the Carbon Sequestration Program.

The Program Opportunity

The importance of carbon sequestration research has been underscored by the President's Committee of Advisors on Science and Technology (PCAST). The committee's report, *Federal Energy Research and Development for the Challenges of the Twenty-First Century*, recommends increasing yearly budgets for the program "... to the vicinity of tens of millions."

The joint Office of Fossil Energy and Office of Science April, 1999 draft report *Carbon Sequestration: State of the Science* subsequently has assessed "... key areas for research and development (R&D) that could lead to an understanding of the potential for future use of carbon sequestration as a major tool for managing carbon emissions." This program plan builds on these two efforts.

Using present technology, current estimates of sequestration costs are in the range of $100-300/ton of carbon emissions avoided. The program goal is to reduce the cost of carbon sequestration to $10 net per ton of carbon emissions avoided or lower by the year 2015. If this can be achieved, it could save the United States trillions of dollars. Importantly, achieving a mid-point stabilization scenario (e.g., 550 ppm CO_2) does not require wholesale introduction of zero emission systems in the near-term. This is critical to technology development, as it allows time for R&D to work — to develop *cost-effective* technology over the next 10-15 years that could be deployed for (1) new capacity and (2) capital-stock replacement capacity.

R&D Portfolio

The program has six primary elements:

- Separation and Capture
- Sequestration of CO_2 in Geological Formations
- Ocean Sequestration
- Sequestration in Terrestrial Ecosystems
- Advanced Concepts
- Modeling and Assessments

These research pathways stem directly from the *Carbon Sequestration: State of the Science* report. The program portfolio covers the entire carbon sequestration "life cycle" of capture, separation, transport, and storage or reuse, as well as the related research needs for the two other major energy-related greenhouse gases of concern, methane and nitrous oxides.

Program Strategy

A program that encompasses R&D on a diverse portfolio of sequestration technologies offers the best chance of success for reducing risks and ultimate costs to the United States under a carbon-constrained future.

In the near-term, the program will examine and select the *science-based* sequestration approaches that have the most potential to yield the cost-effective technologies that are required. The program has two complementary time frames for its technology *products*. In the mid-term, the program will develop options for "value-added" sequestration with multiple benefits, such as using CO_2 in Enhanced Oil Recovery operations and in methane production from deep, unmineable coal seams. In the long-term, the technology products will be more revolutionary and rely less on site-specific or application-specific factors to ensure their economic viability.

Significant industry participation is essential for all phases of the program, through workshops, advisory panels, competitive awards, and cost-shared partnerships. For example, in FY 1999, a broad-based solicitation for advanced sequestration concepts will be conducted.

Program Benefits

If the program goal (reduce the net cost of carbon sequestration to $10 per ton or lower by 2015) is realized, the potential savings are enormous. Projections of required Federal funding have been developed based on the cost of planned activities identified in the program's ongoing outreach and roadmapping exercises. Under a scenario in which global emissions are reduced to stabilize the atmospheric concentration of CO_2 at 550 ppm, the estimated cumulative benefit of improved sequestration technology to the U.S. economy through 2050 equals $2.7 trillion. A sustained R&D program initiated now will enable low-cost sequestration options to be developed, demonstrated, and ready when and if they are needed.

I. Introduction

This R&D program plan for the Carbon Sequestration Program is based on an ongoing series of collaborative efforts with stakeholders. The program's vision and R&D portfolio, for example, are directly related to the joint DOE Office of Fossil Energy and Office of Science (OS) report on *Carbon Sequestration: State of the Science*. This in turn was driven by the PCAST report, *Federal Energy Research and Development for the Challenges of the Twenty-First Century*. This program plan evolved directly from the PCAST report and the joint FE and OS working paper as shown in Figure 2.

A. Program Drivers

The availability of clean, affordable energy is essential for the prosperity and security of the United States and the world in the 21st century. Today, emissions of CO_2 into the atmosphere are an inherent part of electricity generation, transportation, and building systems. But net increases in CO_2 emissions from energy systems and other human activity may be causing changes in the earth's climate, changes that could be harmful to human health and global economic prosperity. Much uncertainty is associated with the global climate change issue, but it is possible, even likely, that deep cuts in net CO_2 emissions from human activity will be required over the next 50 to 100 years.

Carbon sequestration enables the use of fossil fuels in energy systems without emissions of CO_2 into the atmosphere. It includes capturing CO_2 gas from flue gas and other point sources and sequestering it, as well as reducing atmospheric concentrations by enhancing the uptake of CO_2 through natural sinks (e.g., forests, oceans, microorganisms). The energy sector is responsible for roughly 90 percent of U.S. greenhouse gas emissions, and 85 percent of the current U.S. energy system is based on fossil fuels. Moreover, there are economic and environmental limits on the alternatives of nuclear and renewable-based energy technologies. It is therefore prudent and sensible to invest today in carbon-sequestration R&D to enable the continued use of fossil fuels in a carbon-constrained economy.

There is a growing acceptance within industry, academia, and the general public that carbon-emission-free energy systems, transportation systems, and industrial processes may be necessary. That is, it is accepted that efficiency improvements, use of alternative energy sources, and other incremental changes are not sufficient to stabilize the concentration of CO_2 in the atmosphere. Carbon-sequestration R&D is needed so that the actions required to reduce carbon emissions in the future can be executed with minimal impact on the economy.

Vision Statement

The vision for the program is to possess the scientific understanding of carbon sequestration and develop to the point of deployment those options that ensure environmentally acceptable sequestration to reduce anthropogenic CO_2 emissions and/or atmospheric concentrations.

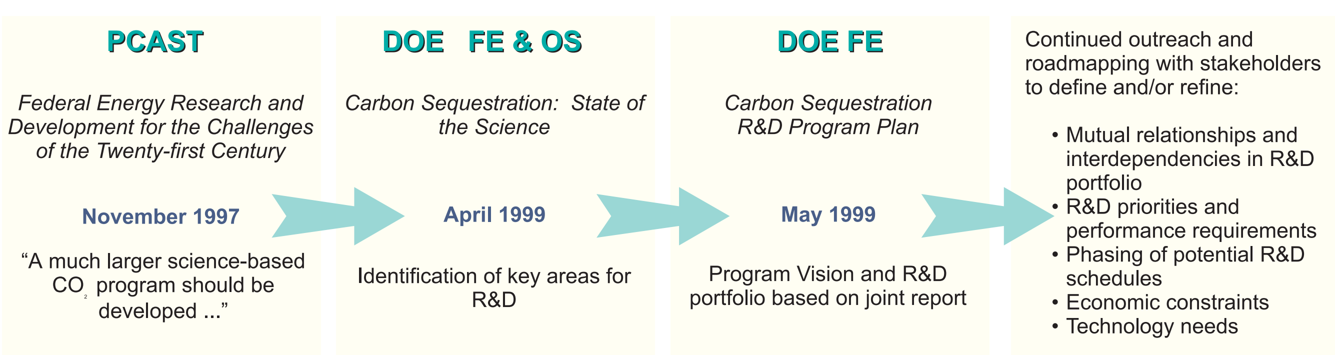


Figure 2. Program Drivers

The importance of carbon sequestration research has been underscored by the PCAST report, which makes the following recommendations for increasing DOE's R&D for carbon sequestration:

"A much larger science-based CO_2 sequestration program should be developed with the budget increasing from the current $1 million per year [FY 1997] to the vicinity of tens of millions."

The report further states:

"The R&D should be supported and managed by FE in collaboration with OS and the USGS. It should also collaborate strongly with international efforts, notably those in Japan and Europe. The aim should be to provide a science-based assessment of the prospects and costs of CO_2 sequestration."

The joint FE and OS report offers a broad vision for new options to curb greenhouse gases. The goal of the report is to ". . . identify key areas for research and development (R&D) that could lead to an understanding of the potential for future use of carbon sequestration as a major tool for managing carbon emissions." The key areas identified for R&D are the basis for the Carbon Sequestration Program's research portfolio.

B. Federal Role

There is a strong role for the federal government in the development of CO_2 capture and sequestration technologies. First, the motivation for sequestration R&D — the greenhouse effect — is inherently a public issue. There are no isolated cause and effect relationships between specific CO_2 emissions sources and local climate effects that could motivate individual action. Second, sequestration R&D is too risky for the private sector. From the PCAST report:

"This is very-high-risk long-term R&D that will not be undertaken by industry alone without strong incentives or regulations, although industry experience and capabilities will be very useful."

The need for federal government leadership in the development of sequestration technology was reiterated by stakeholders at a workshop hosted by the Massachusetts Institute of Technology in June 1998. A working group reached the following conclusion

"Traditional [government/industry]partnerships are not appropriate at this time. We [the private sector] lack the traditional drivers such as a commercial product or a regulatory mechanism."

C. Program Goals

The main challenges for the Carbon Sequestration Program are to reduce the cost of sequestration, develop a broad portfolio of sequestration options, and ensure that long-term sequestration practices are effective and do not introduce any new environmental problems. Various investigators estimate that the level of atmospheric stabilization required is somewhere between 350 ppm and 750 ppm CO_2. Appendix A provides an overview of the emission limits associated with stabilization of ambient CO_2 concentrations. The mid-point of 550 ppm (approximately 1.5 times the current ambient level) has been selected as the baseline scenario in establishing the program's long-term sequestration goals.

The specific goals are:

- Provide economically competitive and environmentally safe options to offset all projected growth in baseline emissions of greenhouse gases by the U.S. after 2010, with offsets starting in 2015
- The long-term cost goal is in the range of $10/ton of avoided net costs for carbon sequestration
- Offset at least one-half the required reductions in global greenhouse gases, measured as the difference in a business-as-usual baseline and a strategy to stabilize concentrations at 550 ppm CO_2, beginning in the year 2025

The latter goal represents the global potential for these technology options if broadly applied by the United States and other countries.

Associated technical objectives are: (1) drive down the cost of CO_2 separation and capture from energy production and utilization systems, (2) establish the technical, environmental, and economic feasibility of carbon sequestration using a variety of storage sites and fossil-energy power systems, (3) determine the environmental consequences of large-scale CO_2 storage, (4) develop opportunities to integrate fossil energy technologies with enhancement of natural sinks, (5) develop innovative technologies that produce valuable commodities from CO_2, and (6) incorporate carbon sequestration processes into advanced energy production and utilization systems.

D. Program Relationships

To achieve any level of atmospheric stabilization, there are three basic options: (1) reduce the carbon content of fuels, (2) improve the efficiency of energy use, and (3) capture and sequester the carbon. The Office of Fossil Energy's Vision 21 program directly addresses the first two. The Carbon Sequestration Program addresses the third option. As shown in Figure 3, the Carbon Sequestration Program's portfolio of activities is closely linked to the Vision 21 Program. Unlike conventional air-combustion energy systems, many of the advanced energy technologies being developed as a part of the Vision 21 Program produce a relatively pure stream of CO_2 that is amenable to capture and sequestration.

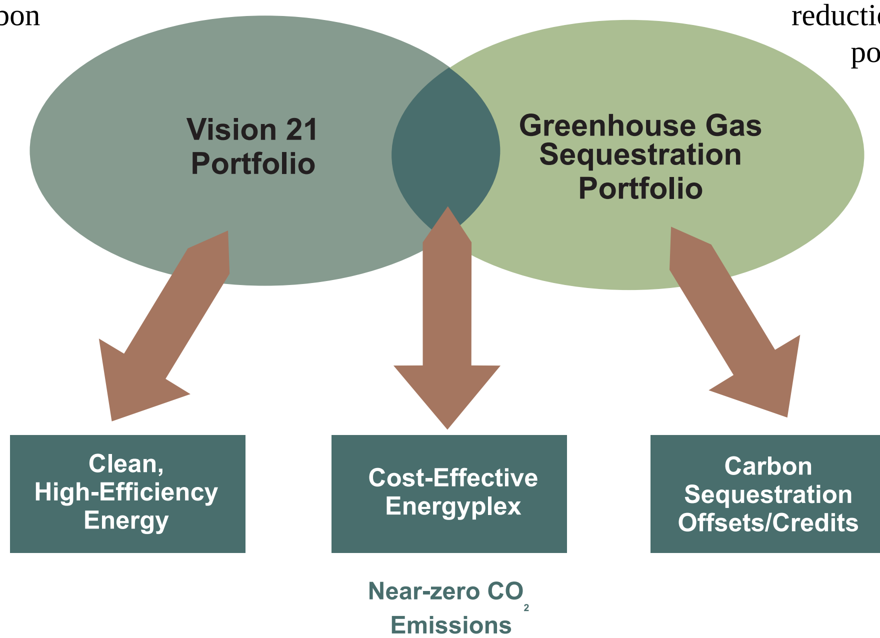


Figure 3. Combined Portfolio Benefits

The development of advanced CO_2 separation technologies under the Carbon Sequestration Program will produce systems that are compatible with the process conditions envisioned for the Vision 21 Program's advanced energy systems.

There is also a strong synergy between the Carbon Sequestration Program and the other elements of the Advanced Research and Environmental Technology (AR&ET) Program, which is focused on innovations that will enable existing and new fossil fuel power plants to operate under increasingly stringent air emissions regulations. Many of the options for capturing CO_2 from flue gas will also capture sulfur dioxide (SO_2), oxides of nitrogen (NO_x), particulates, mercury, and other hazardous air pollutants. For example, "one box" concepts that would combine CO_2 capture with reduction of criteria pollutant emissions could provide highly cost-effective solutions.

With proper planning, the Vision 21, Carbon Sequestration, and AR&ET programs will combine synergistically to produce advanced fossil-based energy systems that cost less, use less fuel, and emit near-zero levels of CO_2 to the atmosphere.

II. Program R&D Portfolio

Based on the report *Carbon Sequestration: State of the Science* and the ongoing roadmapping exercise, the R&D activities are structured around five basic pathways to long-term carbon sequestration:

- Separation and capture
- Sequestration of CO_2 in geologic formations
- Ocean sequestration
- Carbon sequestration in terrestrial ecosystems (soils and vegetation)
- Advanced concepts (chemical, biological and other approaches)

Figure 4 shows that each of the five pathways integrates with the flexible-product, high-efficiency energy-conversion systems being developed in the Vision 21 Program. Together, they cover the entire carbon sequestration "life cycle" of capture, separation, transport, and storage or reuse. An additional program element, modeling and assessments, provides the analysis to define and assess R&D opportunities and pathways within the five main R&D areas, and is critical to portfolio management.

Table 1. Worldwide Capacity of Carbon Reservoirs

Carbon sequestration reservoir	Capacity, GtC
Oceans*	1,400 - $2x10^7$
Geologic structures*	300 - 3,200
Terrestrial systems (forestation and soil)	>100
Fixation and/or re-use (advanced concepts)	??
1990 Global Anthropogenic Emissions, GtC/yr	6.0

* Source: *Carbon Dioxide Disposal from Power Stations*, IEA Greenhouse Gas R&D Programme, 1998; Carbon Management, Assessment of Fundamental Research Needs, DOE Office of Science.

Capacity estimates for the various sequestration reservoirs are presented in Table 1 in giga tonnes of carbon (GtC, billions of metric tons of carbon). As a first evaluation criterion, the sequestration pathways being pursued by the program should have a large CO_2 storage capacity compared to the rate of anthropogenic emissions. Table 1 shows that this is true, even though a large degree of uncertainty is associated with the capacity estimates. Moreover, carbon can be sequestered in various forms. Table 2 shows the volume densities of various forms of carbon.

R&D and modeling and assessment activities conducted by the program over the next few years will be aimed at firming up estimates of sequestration potential for each of the five R&D pathways. The estimate for sequestration potential will likely increase as reliable

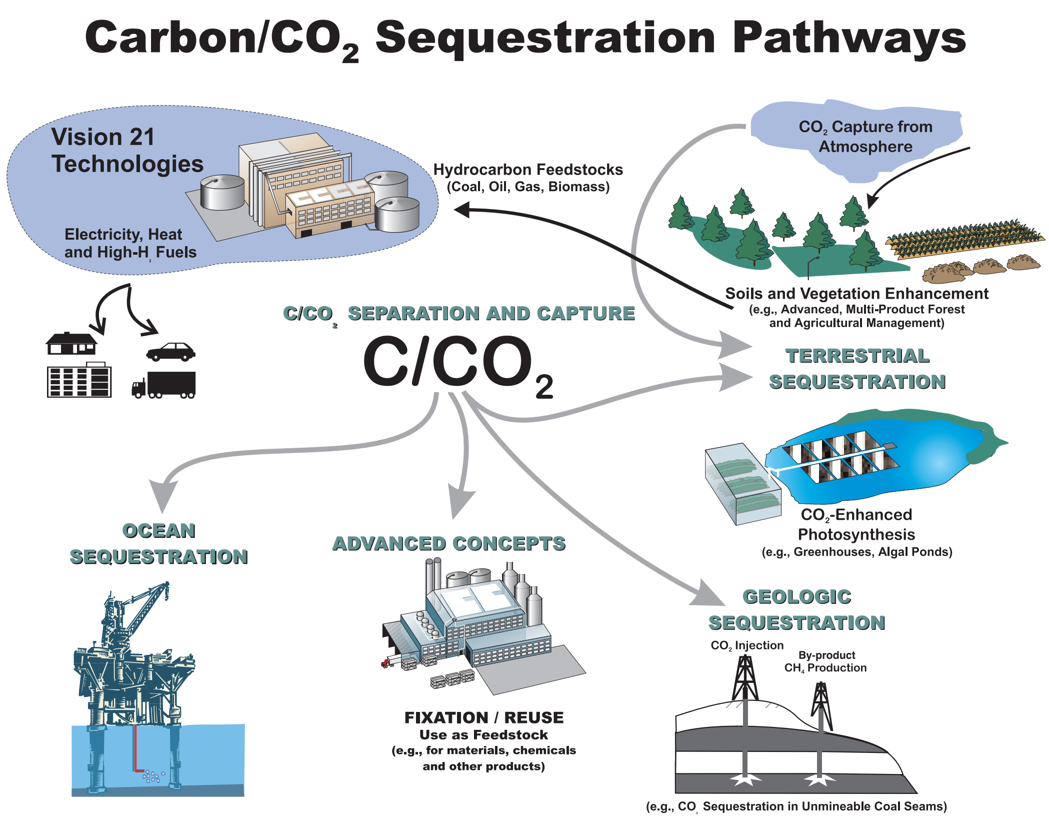


Figure 4. Carbon Sequestration Pathways

Table 2. Volume Densities of Various Forms of Carbon (kg carbon/m³)

CO_2 gas (60 F, 100 psi)	3
CO_2 clathrate	81
Biomass (poplar wood)	220
CO_2 liquid	253
CO_2 solid	425
Magnesium carbonate	432

estimates for terrestrial and reuse options are developed, and as improved approaches and new opportunities are identified.

The program consists of six elements, one for each of the five R&D pathways and a sixth modeling and assessment element. Each is described below in general terms. Appendix B presents a list of ongoing and planned activities for each program element in FY1999 and FY2000.

A. Separation and Capture

Before CO_2 gas can be sequestered from point sources, it must be captured as a relatively pure gas. On a mass basis, CO_2 is the 19th largest commodity chemical in the United States, and CO_2 is routinely separated and captured as a by-product from industrial processes such as synthetic ammonia production, H_2 production, and limestone calcination. Figure 5 is a picture of a large-scale CO_2 production unit.

However, existing capture technologies are not cost-effective when considered in the context of CO_2 sequestration. Analysis performed by SFA Pacific, Inc. indicates that adding existing technologies for CO_2 capture to an electricity generation process increases the cost of electricity by 2.5 cents to 4 cents/kWh depending on the type of process. Further, carbon dioxide capture is generally estimated to represent three-fourths of the total cost of a carbon capture, storage, transport, and sequestration system.

The program will pursue evolutionary improvements in existing CO_2 capture systems and also explore revolutionary new capture and sequestration concepts. The most likely options currently identifiable for CO_2 separation and capture include the following:

- Absorption (chemical and physical)
- Adsorption (physical and chemical)
- Low-temperature distillation
- Gas separation membranes
- Mineralization and biomineralization

Opportunities for significant cost reductions exist since very little R&D has been devoted to CO_2 capture and separation technologies. Several innovative schemes have been proposed that could significantly reduce CO_2 capture costs, compared to conventional processes. "One box" concepts that combine CO_2 capture with reduction of criteria-pollutant emissions will be explored as well.

Figure 5. CO_2 Separation in Hydrogen Production

Examples of activities for this program element include:

- Develop revolutionary improvements in CO_2 separation and capture technologies
  - new materials (e.g., physical and chemical absorbents, carbon fiber molecular sieves, polymeric membranes)
  - micro-channel processing units with rapid kinetics
  - CO_2 hydrate formation and separation processes
  - oxygen-enhanced combustion approaches
- Provide retrofittable CO_2 reduction and capture options for existing large point sources of CO_2 emissions such as electricity generation units, petroleum refineries, and cement and lime production facilities
- Integrate CO_2 capture with advanced power cycles and technologies and with environmental control technologies for criteria pollutants

B. Sequestration of CO_2 in Geologic Formations

CO_2 sequestration in geologic formations includes oil and gas reservoirs, unmineable coal seams, and deep saline reservoirs.

Oil and gas reservoirs. In some cases, production from an oil or natural gas reservoir can be enhanced by pumping CO_2 gas into the reservoir to push out the product, which is called enhanced oil recovery (EOR). Although the low market price for oil and natural gas has limited the incentives for such measures, the United States is the world leader in EOR technology, using about 32 million tons of CO_2 per year for this purpose.

From the perspective of the Sequestration Program, EOR represents an opportunity to sequester carbon at low net cost, due to the revenues from recovered oil/gas. In an EOR application, the integrity of the CO_2 that remains in the reservoir is well-understood and very high, as long as the original pressure of the reservoir is not exceeded. The scope of this EOR application is currently economically limited to point sources of CO_2 emissions that are near an oil or natural gas reservoir. Still, EOR represents an exciting opportunity for near-term, low-cost sequestration.

Coal Bed Methane. Coal beds typically contain large amounts of methane-rich gas that is adsorbed onto the surface of the coal. The current practice for recovering coal bed methane (CBM) is to depressurize the bed, usually by pumping water out of the reservoir. An alternative approach is to inject carbon dioxide gas into the bed, as shown graphically in Figure 6. Tests have shown that CO_2 is roughly twice as adsorbing on coal as methane, giving it the potential to efficiently displace methane and remain sequestered in the bed. CO_2 recovery of CBM has been demonstrated in limited field tests, but much more work is necessary to understand and optimize the process.

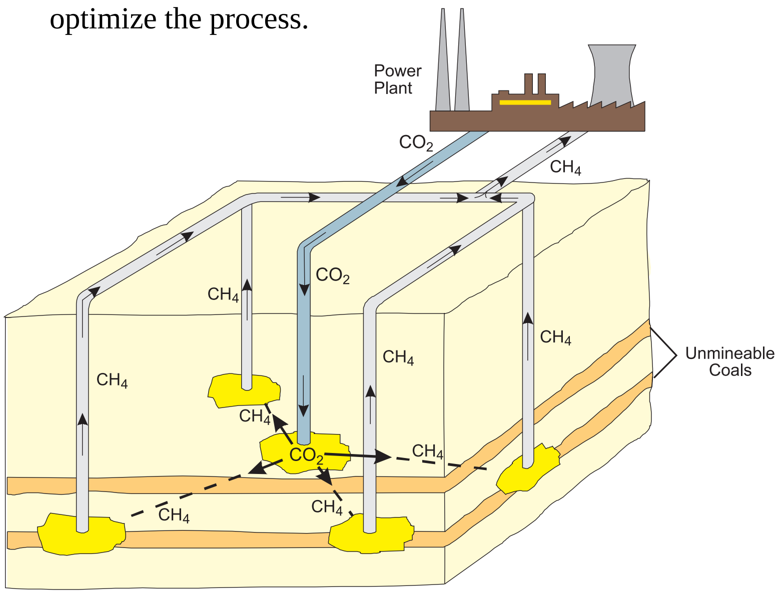


Figure 6. Coal Bed Methane Production - CO_2 Storage Concept

Similar to the by-product value gained from EOR, the recovered methane provides a value-added revenue stream to the carbon sequestration process, creating a low net cost option. Work is needed to develop better estimates of the potential capacity of cost-effective coal bed sequestration in the United States, although the capacity is potentially high. The U.S. coal resources are estimated at 6 trillion tons, and 90 percent of it is unmineable due to seam thickness, depth, and structural integrity. Another promising aspect of CO_2 sequestration in coal beds is that many of the large unmineable coal seams are near electricity-generation facilities that are large point sources of CO_2 gas. Thus, limited pipeline transport of CO_2 gas would be required. Integration of coal bed methane with a coal-fired electricity generation system can provide an option for additional power generation with low emissions.

Saline Formations. Sequestration of CO_2 in deep saline formations does not produce value-added by-products, but it has other advantages. First, the estimated carbon storage capacity of saline formations in the United States is large, making them a viable long-term solution. Bergman and Winter have estimated that deep saline formations in the United States could potentially store up to 500 GT of CO_2. Second, most existing large CO_2 point sources are within easy access to a saline formation injection point (no pipelines required), and therefore sequestration in saline formations is compatible with a strategy of transforming large portions of the existing U.S. energy and industrial assets to near-zero carbon emissions via low-cost carbon sequestration retrofits.

Assuring the environmental acceptability and safety of CO_2 storage in saline formations is a key component of this program element. Determining that CO_2 will not escape from formations and either migrate up to the earth's surface or contaminate drinking water supplies is a key aspect of sequestration research. The program will conduct fundamental research and field testing to develop the capability to predict the stability of CO_2 within saline formations.

Although much work is needed to better understand and characterize sequestration of CO_2 in deep saline formations, a significant baseline of information and experience exists. For example, as part of EOR operations, the oil industry routinely injects brines from the recovered oil into saline reservoirs, and the U.S. Environmental Protection Agency (EPA) has permitted some hazardous waste disposal sites that inject liquid wastes into deep saline formations.

The Norwegian oil company, Statoil, is injecting approximately one million tonnes per year of recovered CO_2 into the Utsira Sand, a saline formation under the sea associated with the Sleipner West Heimdel gas reservoir. The amount being sequestered is equivalent to the output of a 150-MW coal-fired power plant. This is the only commercial CO_2 geological sequestration facility in the world.

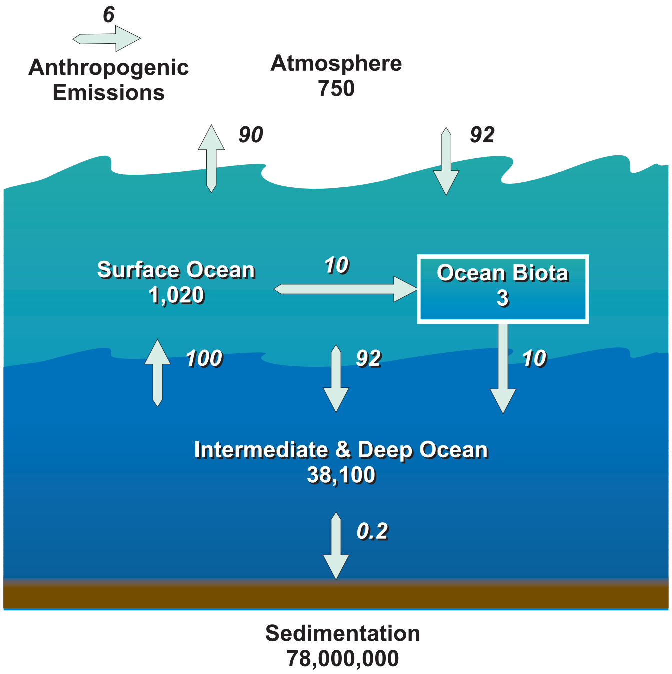
The thrust of this program element is to conduct fundamental studies and field tests to measure the degree to which the CO_2 stays sequestered in the formations and to assess any long-term ecological impacts. Experience must be gained in a number of critical areas. The primary foci for R&D on sequestration in geologic formations include:

- Develop better estimates of the potential capacity for coal bed methane and deep saline formations
- Improve the percent of CO_2 input into an EOR process that remains sequestered in the reservoir
- Develop reliable and cost-effective systems for monitoring CO_2 migration in the subsurface
- Assess and ensure long-term stability of sequestered CO_2
- Reduce the cost and energy requirements of CO_2 sequestration in geological formations
- Ensure that geological sequestration will not create adverse environmental legacies in the future

C. Ocean Sequestration

CO_2 is soluble in ocean water, and through natural processes the oceans both absorb and emit huge amounts of CO_2 into the atmosphere. Figure 7 shows the fluxes associated with the ocean carbon cycle.

It is widely believed that the oceans will eventually absorb most of the CO_2 in the atmosphere above the pre-industrial level of 288 ppm. However, the kinetics of ocean uptake are unacceptably slow, causing a peak in atmospheric CO_2 concentration of several hundred years. The program will explore options for speeding up the natural processes by which the oceans absorb CO_2 and for injecting CO_2 directly into the deep ocean.



Reservoirs - billions of tonnes of carbon

Fluxes - bilions of tonnes of carbon per year

Source: "Atmospheric Carbon Dioxide and the Ocean," Siegenthaler and Sarmiento, *Nature* volume 365, pp 119-125.

Figure 7. The Ocean Carbon Cycle

One approach to enhancing the rate of CO_2 absorption in the ocean involves adding combinations of micronutrients and macronutrients to those ocean surface waters deficient in such nutrients. The objective is to stimulate the growth of phytoplankton, which are expected to consume greater amounts of carbon dioxide. When carbon is thus removed from the ocean surface waters, it is ultimately replaced by CO_2 drawn from the atmosphere. The extent to which the carbon from this increased biological activity is sequestered is unknown at this point.

Technology exists for the direct injection of CO_2 into deep areas of the ocean; however, the knowledge is not adequate to optimize the costs, determine the effectiveness of the sequestration, and understand the resulting changes in the biogeochemical cycles of the ocean.

To assure environmental acceptability, developing a better understanding of the ecological impacts of both ocean fertilization and direct injection of CO_2 into the deep ocean is a primary focus of this program element. It is known that small changes in biogeochemical cycles may have large consequences, many of which are secondary and difficult to predict. Of particular concern is the effect of CO_2 on the pH of ocean water.

Examples of activities for this program element include:

- Better define the enhancement of natural carbon sequestration, such as the process of fixation by phytoplankton
- Determine the potential consequences of large-scale ocean fertilization on the biosphere and on biogeochemical cycling, and optimize fertilizer design and delivery
- Conduct field tests to determine the potential consequences of injecting CO_2 into the deep ocean and to develop reliable estimates of the cost and effectiveness of ocean sequestration
- Investigate concepts for converting CO_2 to other forms of carbon (e.g., carbonates) that are stable in the ocean

D. Carbon Sequestration in Terrestrial Ecosystems (soils and vegetation)

Enhancing the natural processes that remove CO_2 from the atmosphere is thought to be one of the most cost-effective means of reducing atmospheric levels of CO_2, and forestation and deforestation abatement efforts are already under way. This program element is focused on integrating measures for improving the full life-cycle carbon uptake of terrestrial ecosystems, including farmland and forests, with fossil fuel production and use.

Examples of activities for this program element include:

- Facilitate partnerships between energy producers (e.g., coal companies, utilities), land owners, the biomass and biofuels industries, and government agencies such as the U.S. Forestry Service to determine approaches to increase carbon equestration in soils and vegetation
- Provide comprehensive evaluations and assessments of the full life-cycle costs associated with integrated energy production and utilization and enhanced terrestrial sinks
- Identify ways in which coal combustion by-products can contribute to increased terrestrial sequestration.
- Develop innovative and advanced concepts that integrate energy production with approaches to enhance natural terrestrial sinks

This program element is being conducted in collaboration with the DOE Office of Science, and the U.S. Forest Service of the U.S. Department of Agriculture.

E. Advanced Concepts (chemical, biological, and other approaches)

Recycling or reuse of CO_2 from energy systems would be an attractive alternative to storage of CO_2. The goal of this program element is to reduce the cost and energy required to chemically and/or biologically convert CO_2 into either commercial products that are inert and long-lived or stable solid compounds.

Two promising chemical pathways are magnesium carbonate and CO_2 clathrate, an ice-like material. Both provide quantum increases in volume density compared to gaseous CO_2, as shown in Table 2. As an example of the potential of chemical pathways, the entire global emissions of carbon in 1990 could be contained as magnesium carbonate in a space 10 km by 10 km by 150 m.

Concerning biological systems, incremental enhancements to the carbon uptake of photosynthetic systems could have a significant positive effect. Also, harnessing naturally occurring, non-photosynthetic microbiological processes capable of converting CO_2 into useful forms, such as methane and acetate, could represent a technology breakthrough. An important advantage of biological systems is that they do not require pure CO_2 and do not incur costs for separation, capture, and compression of CO_2 gas.

This program element will seek to develop novel and advanced concepts for capture, reuse, and storage of CO_2 from energy production and utilization systems based on, but not limited to:

- Biological systems
- Advanced catalysts for CO_2 or CO conversion
- Novel solvents, sorbents, membranes and thin films for gas separation
- Engineered photosynthesis systems
- Non-photosynthetic mechanisms for CO_2 fixation (methanogenesis and acetogenesis)
- Ways for genetic manipulation of agricultural and trees to enhance CO_2 sequestering potential
- Advanced decarbonization systems
- Biomimetic systems

F. Modeling and Assessments

Better assessments of the costs, risks, and the potential of carbon sequestration technology are essential to develop technological options for greenhouse gas mitigation. Sound assessment capabilities are required to evaluate technological options in a total systems context, considering costs and impacts over a full product cycle, and societal and environmental effects to provide a basis for assessing trade-offs between local environmental impacts and global impacts. Analytical tools are needed to strategically select the most promising R&D efforts that have high potential, but significant uncertainties, associated with their costs and effectiveness.

Examples of activities for this program element include:

- Adapt existing oil and gas reservoir models used for fossil fuel production to carbon sequestration
- Develop risk assessment models and life-time prediction models for geologic and ocean sequestration
- Assess the capacities of geologic and ocean storage sites
- Provide verification for the sequestration capabilities of various technological options
- Develop criteria to guide selection of potential storage sites, including enhancing natural sinks, and permit uniform assessments of the carbon mitigation potential of novel and advanced systems
- Model naturally occurring CO_2 formations and processes to yield information that could serve as analogs for estimating the long-term CO_2 storage potential of depleted oil and gas reservoirs, and other approaches

G. Schedule of Near-term Activities

Figure 8 identifies major milestones for the Carbon Sequestration Program. As noted previously, Appendix B contains a list of ongoing and planned activities for each program element in FY 1999 and FY 2000.

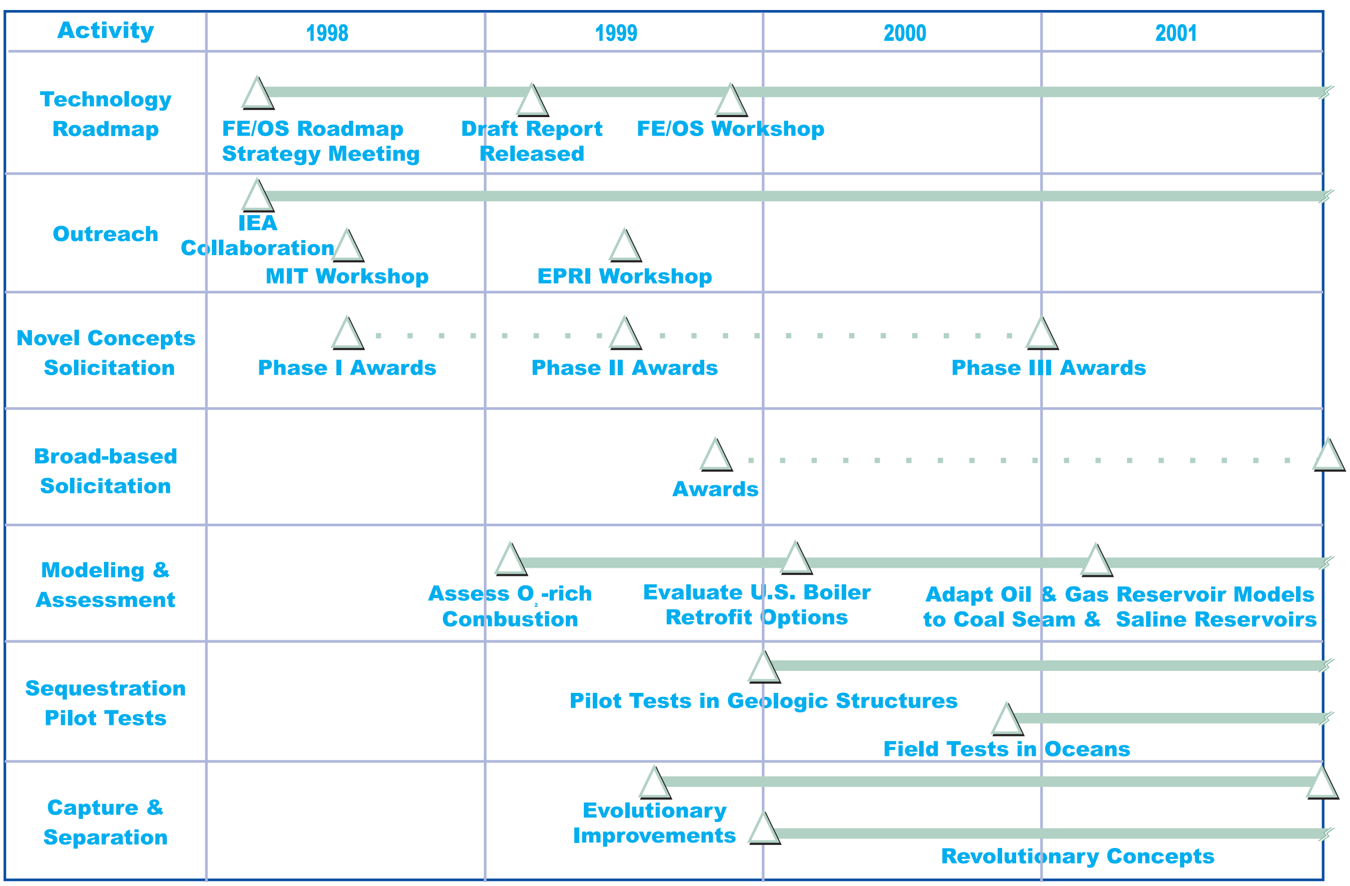


Figure 8. Carbon Sequestration Program Milestone Chart

III. Program Management

Management of the Carbon Sequestration Program is based on a strong stakeholder outreach effort and a portfolio approach to selection of R&D topics. The program strategy, timing, and costs are based on this collaborative approach. Figure 9 shows the program's major phases and projected budget.

A. Program Strategy and Timing

A program that encompasses R&D on a diverse portfolio of sequestration technologies offers the best chance of success, both in reducing risks and ultimate costs to the United States under a carbon-constrained future. In the near-term, the program will examine and identify a spectrum of *science-based* sequestration approaches that have the greatest potential to yield the cost-effective technologies that are required.

The program has two complementary time frames for its technology *products*. In the mid-term, the program will develop options for "value-added" sequestration with multiple benefits, such as using CO_2 in EOR operations and in methane production from deep, unmineable coal seams. In the long-term, the technology products will be more revolutionary, relying less on site-specific or application-specific factors to ensure their economic viability over the carbon sequestration "life cycle" of capture, separation, transportation, and storage or reuse.

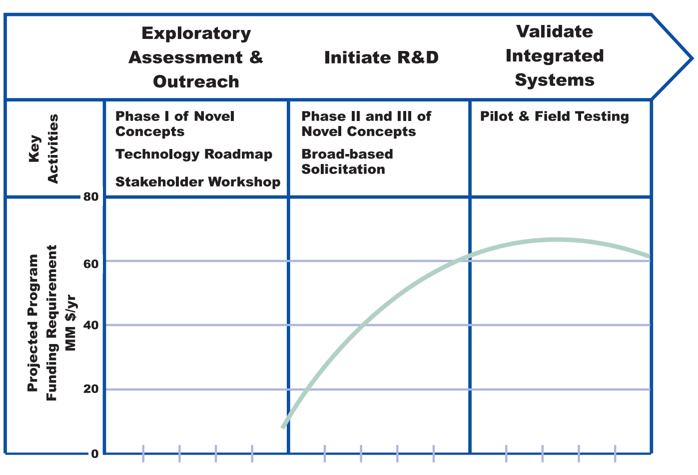


Figure 9. Program Phases and Projected Budget

Carbon Sequestration Program Portfolio Criteria

- *Sequestration potential.* The maximum expected emission reduction or offset of greenhouse gas, expressed in millions of tons per year of carbon equivalent.
- *Low cost.* The expected cost of the commercial sequestration technology, expressed in dollars per ton of carbon equivalent emission avoided.
- *Environmental acceptability.* The expected compatibility of the sequestration technology with the environment, including protection of human health and sensitive ecosystems.
- *Likelihood of success.* The probability of meeting the performance objectives of the research activity.
- *Program balance.* The degree to which the activity complements the scope, timing, risk, and diversity of the sequestration portfolio.
- *Program enhancement.* The degree to which the activity identifies and makes progress on new concepts, thereby increasing the likelihood of a successful sequestration program.
- *Multiple benefits.* The degree to which the activity is likely to produce other benefits, in addition to sequestration.
- *Flexibility.* The ability of the technology to address different types of emission sources.
- *Partnerships.* The participation (financial, intellectual, and programmatic) of other research sponsors, including industry and international partners.
- *R&D cost.* The anticipated expense for conducting laboratory experiments and field tests compared to the potential impact.
- *Leveraging.* The aggregate cost-sharing by non-Fossil Energy participants.
- *Visibility*. The potential for the activity to attract favorable attention to the Fossil Energy sequestration R&D program.

B. Portfolio Approach to Management

The program activities are managed as a portfolio, recognizing that knowledge about this field of science and technology is in its infancy and is rapidly evolving. By applying portfolio theory to the management of program resources, the probability of success in achieving program goals is increased.

The program will primarily select research topics and projects through competitive solicitations involving industry, university, and national laboratory performers. For example, in FY 1999, a broad-based solicitation will be conducted for new projects and advanced concepts. This will draw on the information from the modeling and assessment activities, the ongoing roadmapping activity, and the results of international collaborative assessments carried out by the International Energy Agency.

C. Stakeholder Outreach and Partnerships

Since the initiation of the Carbon Sequestration Program in 1998, outreach and planning exercises have been conducted to help determine appropriate direction and focus for the management of the R&D activities. In collaboration with DOE's Office of Science, the report *Carbon Sequestration: State of the Science* was developed and identifies the five major areas of needed R&D that serve as the basis for the program.

The program is focused on strong industry participation in R&D activities. This is challenging considering the lack of commercial drivers or regulatory requirements for carbon sequestration technologies, and innovative partnerships among government, industry, and academia will be required. In 1998, a workshop was conducted at the Massachusetts Institute of Technology to elicit industry input with respect to which activities were most needed and to raise industry's interest in participating in the program R&D activities (see the box below for a summary of this meeting).

Continued collaborative activities and workshops are essential to keep all stakeholder groups — industry, end-user, non-profit organizations, academia, national laboratories, the environmental community, and government — apprised of new

Stakeholder's Workshop on Carbon Sequestration

In June 1998, the Massachusetts Institute of Technology (MIT) Energy Laboratory hosted a *Stakeholders Workshop on Carbon Sequestration* for the Department of Energy. The workshop had over 100 participants from industry, universities, and government. Industry comprised the largest group of participants. The primary objectives of the workshop were to:

- update stakeholders on the latest developments concerning carbon sequestration,
- solicit stakeholder input on research and development priorities for carbon sequestration, and
- identify possible industry/government/university partnerships.

The workshop's three working groups were organized around three industries: coal, electricity, and oil and gas. Each group addressed the role of carbon sequestration, R&D priorities, partnerships, and the path forward. Some of the common insights and observations made by the three workshop groups included the following:

- A strong federal role is needed. The private sector lacks the traditional drivers such as a commercial product or a regulatory mechanism.
- There is a need for a better assessment of the costs, risks, and potential of sequestration technology.
- Approaches are needed that are innovative and novel; incremental changes will not yield the necessary results.
- A broad range of environmental science and process-oriented technological research should be pursued, from which — as science improves and technological opportunities become apparent — a more focused set of development and demonstration programs can be implemented.
- Advanced carbon dioxide separation technology is a high-priority R&D need.
- The integration of processes covering fossil fuel use (both current and innovative systems), separation, and sequestration is essential to overall system effectiveness, efficiency, and costs. One example is synergy between advanced combustion and capture.
- There is the requirement for an improved fundamental understanding of the natural carbon cycle, of the long-term environmental effects of carbon sequestration pathways, and of other areas to underpin technology development.
- Cost-effectiveness will "bound" technology options.
- Decision makers and the public are not well-informed about carbon sequestration options; outreach and publicity are needed to more broadly disseminate information.

The workshop proceedings may be obtained through the MIT Energy Laboratory web site at http://web.mit.edu/energylab/www/energylb.htm.

developments and to maintain an open dialogue on the merits of carbon sequestration. Table 3 summarizes the outreach accomplishments achieved in 1998 and the activities planned in 1999. In 1999 the program is building on the outreach accomplishments of 1998. For example, several workshops will focus on specific technical issues identified in the general planning exercises conducted in 1998.

International collaborations are another key to developing technology options for mitigating global emissions of greenhouse gases. At present, the United States lags behind other countries in developing and implementing carbon sequestration technologies. Program interactions include work with international research groups such as the International Energy Agency (IEA) Greenhouse Gas R&D Programme, and the Climate Technology Initiative (CTI) of the Framework Convention on Climate Change (FCCC).

Significant cost-sharing and technology transfer to the United States are possible through international agreements. These include the cooperative research among the United States, Japan, and Norway on deep ocean storage of CO_2, and the United States and Canadian project on CO_2 sequestration in deep, unmineable coal seams accompanied by coal bed methane production. Other international collaborative opportunities exist and must be pursued in the interest of achieving global participation in addressing these concerns.

D. Program Costs

Projections of the required funding levels have been prepared from the estimated cost of activities necessary to achieve program goals, and as identified in the technology roadmapping exercises conducted by the program. The budget request for FY 2000 is $9 million and is projected to increase to $24 million in FY 2001. Table 4 shows the required annual program funding for the next 10 years.

Table 3. Carbon Sequestration Program Outreach Activities

1998	1999
In a collaborative effort with DOE's Office of Science, conducted a series of technology roadmapping workshops to identify R&D pathways to meet the program goals	Follow-up workshops on the evolving science and technology roadmap to obtain further stakeholder input and priorities for carbon sequestration
Held a Stakeholders Workshop on Carbon Sequestration hosted by the MIT Energy Laboratory	A workshop jointly sponsored by FETC and EPRI with the electric generation industry
Co-funded the 4th International Conference on Greenhouse Gas Control Technologies (GHGT-4), a part of the IEA Greenhouse Gas R&D Programme	A geologic storage-experts workshop hosted by FETC in collaboration with industry and the IEA Greenhouse Gas R&D Programme
The Vision 21 Stakeholder Workshop held in Pittsburgh, Pennsylvania, included a breakout group focused on Vision 21 needs if a greenhouse gas-constrained future becomes a reality	Jointly sponsored industry/government workshop on CO_2 capture from power generation for reuse in EOR operations
Disseminated a broad range of information about carbon dioxide capture and sequestration technology and also about international collaborative research projects through two Internet websites: FETC: *http://www.fetc.doe.gov* IEA: *http//www.ieagreen.org.uk*	Participation in and organization of special sessions on greenhouse gas management at industry-sponsored conferences and symposia Joint sponsorship of other workshops with the IEA Greenhouse Gas R&D Programme, and the CTI of the FCCC Expansion of the FETC website coverage of carbon sequestration developments

Table 4. Profile of Funding Required to Achieve Program Goals for the Carbon Sequestration Program (millions of dollars per year)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Total	**9.1**	**24**	**33**	**48**	**56**	**64.5**	**63.5**	**67**	**67**	**63.5**	**62**

Figure 10 illustrates the program's projected funding profile through 2010 according to the scale of the projects and the necessary assessment activities in the program portfolio. The required funding to achieve the program goals increases as the program moves from a focus on planning, outreach, and analysis, to initiation of a portfolio of novel concepts and bench-scale work, followed by field tests and large-scale projects. Over the next five years, emphasis will be on the modeling and evaluation of advanced combustion options, studies on novel sequestration concepts, pilot testing of concepts at geologic and oceanic sites, and the development of revolutionary technology to reduce the prohibitive costs of capturing and separating CO_2.

A significant portion of the program's funds are awarded to industry through competitive solicitations. In 1998, the program issued a solicitation for "novel concepts" and made 12 awards from a field of 62 proposals. In FY 1999 six of the most promising projects were selected for Phase II funding. The program plans to issue a broad, multiphase solicitation on advanced sequestration concepts in FY 1999.

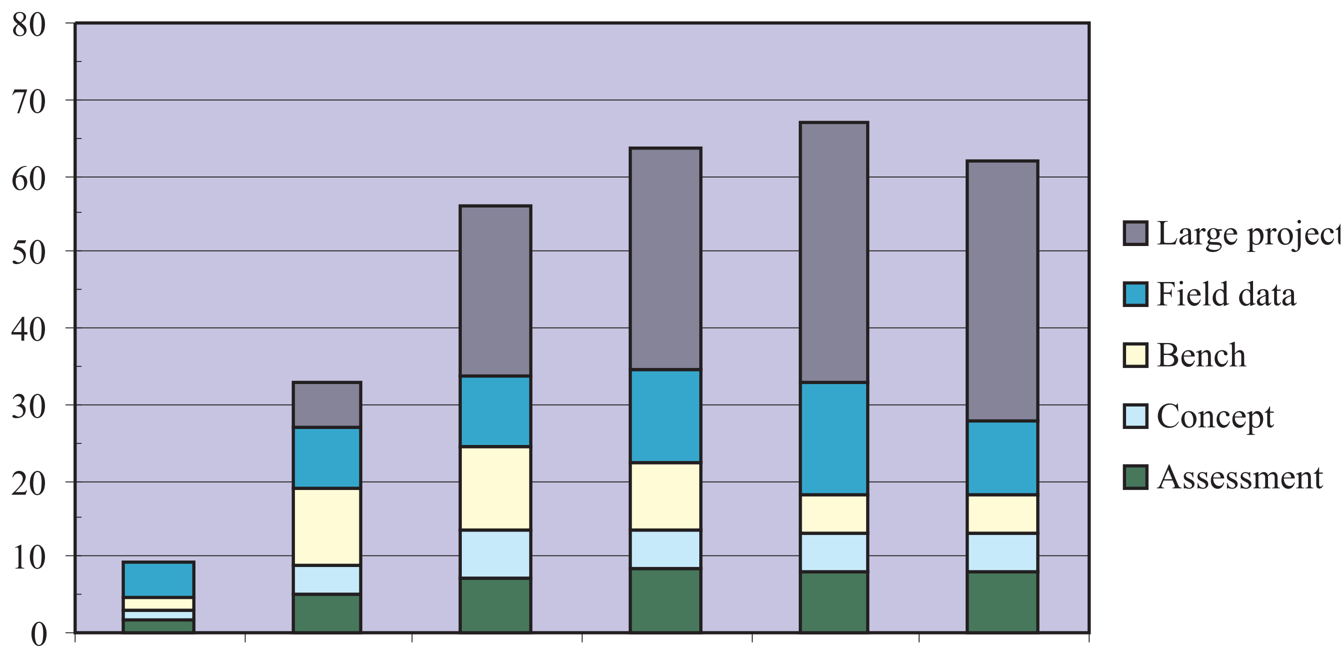


Figure 10. Program Funding Profile

IV. Program Benefits

The program managers have estimated the benefits that the United States could realize over the next 50 years from R&D on carbon sequestration. The primary objective of this R&D is to lower the cost of reducing carbon emissions. The estimated program benefits (in dollars) equal the difference between the aggregate cost of U.S. carbon-emissions reductions with and without improved sequestration technology under various greenhouse gas stabilization scenarios.

If the program's goals are achieved, the cumulative program benefits through 2050 are estimated to be $2.7 trillion, under a scenario of stabilizing the atmospheric concentration of CO_2 at 550 ppm. This is a very large number due to (1) the magnitude of carbon-emissions reductions projected under the 550 ppm CO_2 stabilization scenario, and (2) the relatively high cost of achieving deep carbon emissions reductions with non-sequestration options (conservatively estimated at $300 per metric ton of carbon[1]). A more detailed discussion of the analysis is presented at the end of this section.

The program benefits estimate is highly sensitive to the atmospheric CO_2 stabilization scenario. Table 5 shows the estimated percent reduction in U.S. emissions in 2050 below a business-as-usual scenario for CO_2 concentration targets of 450 ppm, 550 ppm, and 650 ppm. Compared to the base case 550 ppm scenario, the amount of emissions reductions required doubles in the 450 ppm scenario and decreases 50% in the 650 ppm scenario. In the 450 ppm scenario, the cumulative program benefits through 2050 increase from $2.7 trillion to $8.7 trillion, assuming all the incremental CO_2 emissions reductions beyond what is required in the base case analysis are achieved with sequestration technology. In the 650 ppm scenario, benefits through 2050 are substantially lower since, as shown in Figure 11, the deepest reductions occur after 2050.

Figure 11 shows that the program's benefits are also highly sensitive to (1) maintaining the schedule so that *cost-effective* sequestration technologies are ready when they may be needed, and (2) having a diverse portfolio of technology options that can meet 100 percent of market requirements rather than only 50 percent. A broad range of activities is needed to ensure that sequestration options will be available for the many varied energy systems and locations.

[1]Equivalent 82 % per metric ton of CO_2.

Table 5. Benefits Under Different Carbon Emissions Reduction Scenarios

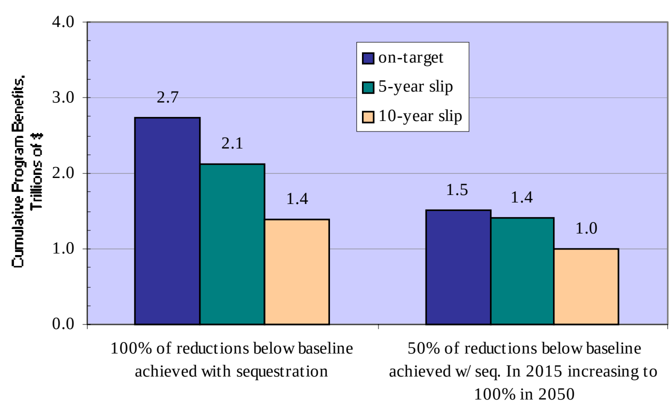
WRE Global Greenhouse Gas Stabilization Scenario*	450 ppm	550 ppm	650 ppm
Percent reduction in U.S. emissions in 2050 below the AEO 99 reference case extrapolated**	64%	31%	20%
Cumulative Program Benefits (Trillion $)	8.7	2.7	0.4

* See Appendix A for a discussion of global greenhouse gas stabilization scenarios

** See the text box on the next page for a discussion of the different U.S. carbon emissions scenarios

The estimated program benefits are not highly sensitive to the program's cost goal of $10/ton of carbon emissions avoided. In the base-case analysis, if the cost is $25/ton, the program benefits decrease from $2.7 trillion to $2.5 trillion, all else being equal.

The Carbon Sequestration Program benefits analysis will be refined on an ongoing basis as new and better data become available and are integrated with other analyses being conducted within the Office of Fossil Energy.



Benefits based on WRE 550 ppm scenario, U.S. carbon emissions through 2050; carbon emissions are reduced below the baseline to offset growth in emissions after 2010; baseline carbon emissions are the EIA high technology forecast extrapolated; 0% discount rate; carbon sequestration cost of 10$/t; marginal cost of emissions reduction below baseline without carbon sequestration of 300 $/tC.

Figure 11. Sensitivity of Benefits to Schedule Slip and Market Share

Conservative Assumptions Are Used in the Benefits Analysis

To quantify the magnitude of future U.S. carbon-emissions reductions, one needs to first define a baseline scenario. The level of reductions equals the difference between the baseline scenario and the assumed reduction scenario.

Figure 12 shows three projections of future U.S. carbon emissions. The highest projection is the reference case of emissions from the *Annual Energy Outlook 1999* (AEO 99) extrapolated through 2050. The middle projection shown in Figure 12 is the "high technology" projection from the AEO 99, with an assumed decrease in the rate of emissions growth after 2020. Regarding the transportation, industrial, commercial, and residential end-use sectors, EIA describes the high technology case as being based on

"... the potential impacts of increased research and development for more advanced technologies ... earlier years of introduction, lower costs, higher maximum market potential, and higher efficiencies than in the reference case."

The lowest emissions line in Figure 12 is a "reduced emissions" scenario that is consistent with the first program goal, " ... offset all projected growth in baseline emissions of greenhouse gases by the U.S. after 2010 ..." Thus the base-case analysis is consistent with achieving the program goals.

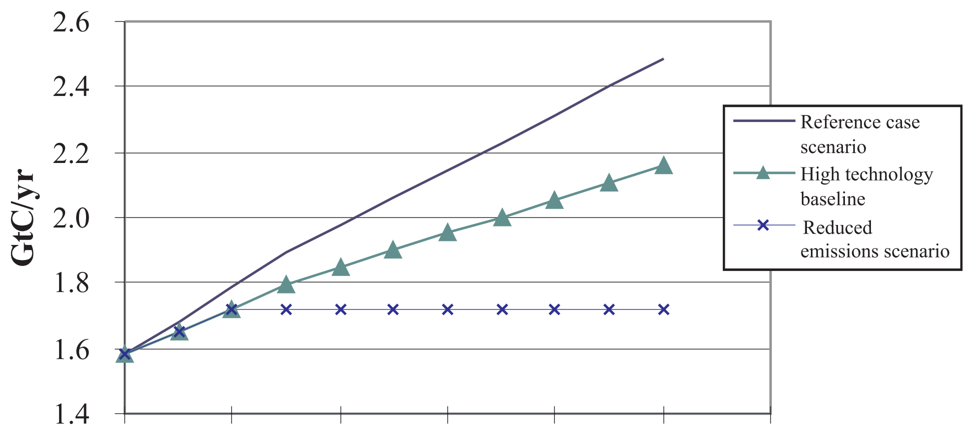


Figure 12. U.S. Carbon Emissions Scenarios

We make the linking assumption that the U.S. carbon emissions under the "reduced emissions" scenario in Figure 12 (i.e., the base-case analysis) are compatible with a global effort to stabilize the concentration of CO_2 in the atmosphere at 550 ppm (based on the WRE analysis; see Appendix A for a discussion of greenhouse gas stabilization). The percentage reduction in U.S. emissions below the reference case (AEO 99 extrapolated) is roughly equal to the percent reduction in global emissions required in the 550 ppm greenhouse gas stabilization scenario. If a higher percentage were assumed for U.S. reductions, the program benefits would increase.

In estimating the magnitude of carbon sequestration requirements, we use the high technology scenario as a baseline. This assumes that a significant amount of the reductions in U.S. carbon emissions below the reference case come from efficiency improvements and alternative energy sources. That is, sequestration is only assumed to be applied after all other alternatives have been fully implemented. If we had assumed that energy efficiency improvements and alternative energy sources played a smaller role in reducing U.S. emissions, the sequestration requirements would increase and the benefits of sequestration technology would be higher.

It is difficult to estimate the cost of achieving deep reductions in emissions below the high technology baseline without sequestration technology, although it is clear it would be very high. For the purposes of this benefits assessment, a low value of $300/metric ton carbon avoided has been assumed to ensure that the estimates of the benefits are conservative. A higher assumed value would increase the benefits. The cost of sequestration equals the program goal, $10/metric ton carbon.

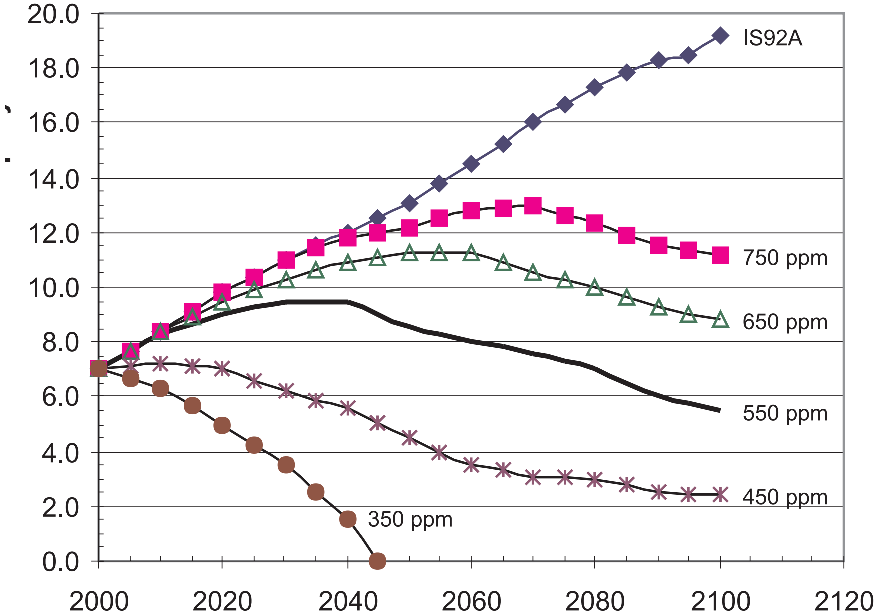
A key assumption employed in calculating the cumulative benefits is the use of a 0% discount rate. This assumption is based on the notion that it may be inappropriate to discount inter-generational environmental benefits.

Regarding the sensitivity of the program benefits to the global CO_2 stabilization scenario, we assume that the high technology baseline scenario is unchanged in the 650 ppm scenario, giving a conservatively low benefits estimate because the drivers for achieving the baseline scenario would be less. We assume all low-cost opportunities for energy efficiency and alternative energy (i.e, options 1 and 2 from the executive summary technical and market challenge) are fully implemented in the base-case scenario. As a result, all incremental carbon emissions reductions required in the 450 ppm scenario are achieved with sequestration systems.

Although the Sequestration Program encompasses CO_2, nitrous oxide, and methane, the program's benefits calculation is based only on reductions in carbon emissions. If nitrous oxide and methane were included, the program's benefits estimate would be higher.

Only emissions reductions within the United States are considered in the benefits calculation. If global applications of sequestration technology were included, the benefits would be higher.

Appendix A. Stabilization of Ambient CO_2 Concentrations



Source: *Nature* , Volume 379, January 18, 1996, pp. 240-243

Figure A1. Implied Anthropogenic Carbon Emissions Through 2100 from the WRE Analysis

Wigley, Richels, and Edmunds (WRE) have produced what is perhaps the definitive work concerning alternative scenarios of the concentration of CO_2 in the atmosphere (*Nature* Vol. 379, January 18, 1996, pp. 240-243). They modeled the natural fluxes of CO_2 in the Earth's ecosystem, and then, based on the volume of the Earth's atmosphere and the ability of natural sinks to absorb excess CO_2 they characterized the relationship between the level of anthropogenic carbon emissions and the atmospheric concentration of CO_2 gas. Figure A1 shows several schedules of global anthropogenic carbon emissions developed by WRE that correspond to sustained atmospheric concentrations of CO_2 between 350 ppm and 750 ppm. As a reference point, the pre-industrial atmospheric concentration of CO_2 was 288 ppm, and today the concentration is 340 ppm. The optimum future concentration of CO_2 in the atmosphere, that which balances the negative climate impacts of the "greenhouse effect" and the cost of reducing carbon emissions, is not known. Many scientists identify the WRE 550 ppm carbon emissions projection as a reasonable target.

The magnitude of change required to achieve a stable concentration of CO_2 in the atmosphere can be gauged by comparing the WRE scenarios to carbon emissions that are projected for a business-as-usual carbon-unconstrained global economy. Figure B1 shows the baseline carbon emissions projection developed by the Intergovernmental Panel on Climate Change. Carbon emissions are projected to increase sharply over the next 100 years, due to population growth and increased energy use in developing nations. Under this baseline scenario, developed countries roughly double their emissions beetween 2000 and 2100, whereas developing country emissions increase by about eight-fold. As a result, the WRE scenarios represent significant emissions reductions below business-as-usual. In 2050, global carbon emissions under the WRE 550 ppm scenario are 34% less than the IS92A projection, and by 2100 the emissions reduction requirements increase dramatically to 70% below the IS92A projection.

Two conclusions can be drawn from the WRE analysis shown in Figure A1. First, limiting the future concentration of CO_2 in the atmosphere to two or even three times the pre-industrial level will require deep reductions in carbon emissions below what would occur in a carbon-unconstrained global economy. Second, there is time (10-30 years) to develop new technologies that can reduce net carbon emissions safely and cost-effectively before deep cuts in carbon emissions are required.

Appendix B. Ongoing and Planned Program Activities for FY 1999 and FY 2000

Carbon Sequestration Program

Activity Area	Objective(s)	FY 1999 Activities	FY 2000 Activities
Separation and Capture	Reduce both the capital and energy costs associated with carbon dioxide capture and separation from large point sources.	• Research initiatives aimed at developing advanced processes, solvents, and sorbents to separate and concentrate CO_2 from energy conversion process streams • Assess CO_2 capture options from IGCC power plants • Membrane development to capture landfill methane for energy production • Development of an advanced CO_2 capture and concentration process based on hydrates	• Evolutionary technological improvements to drive down the costs of CO_2 separation and capture • Revolutionary approaches using advanced processes and materials that integrate CO_2 separation and capture concepts with advanced fossil fuel conversion systems • Development of systems and components that can capture and control emissions of other GHGs, such as methane and nitrous oxide, from energy production technologies
Sequestration in Geologic Formations	Field test and verify storage of carbon dioxide in coal seams and other geologic structures.	• Exploratory research on "value-added" or multiple benefits approaches, such as carbon sequestration coupled with Enhanced Oil and Gas Recovery operations and coal bed methane production • Fundamental investigations into defining the characteristics of coals that enhance CO_2 absorption and storage • Laboratory studies dealing with the storage of CO_2 as mineral carbonates • Mechanistic research on the interaction of CO_2 with minerals in saline reservoirs	• Identify and resolve potential environmental issues concurrently with technology development activities associated with land-based sequestration in deep saline reservoirs and other geologic formations • Develop monitoring and evaluation methodologies to assess the long-term viability of saline reservoir sequestration • Support multiple field testing and verification of CO_2 sequestered via enhanced oil recovery and coal bed methane recovery in different U.S. geological and geographic settings
Ocean Sequestration	Identify the cost, environmental acceptability, and effectiveness of sequestering carbon dioxide in the oceans Develop a better understanding of the ecological impact of injecting carbon dioxide into the deep ocean	• Feasibility study on promoting coral growth and assessments on stimulating CO_2 absorption by the ocean • Technical and environmental planning for ocean injection of liquid CO_2 experiment and supporting tests on formation and stability of CO_2 hydrates	• Scientific experimentation on ocean injection into mid- to deep-ocean environments accompanied by full complement of monitoring and diagnostic capabilities • Continue assessments and conduct testing on enhancing indirect sequestration in the oceans by use of nutrients

Appendix B. Ongoing and Planned Program Activities for FY 1999 and FY 2000

Carbon Sequestration Program			
Activity Area	**Objective(s)**	**FY 1999 Activities**	**FY 2000 Activities**
Carbon Sequestration in Terrestrial Ecosystems (Soils and Vegetation)	Enhance carbon sequestration in trees and other woody plants and also in soils through new agricultural concepts Integrate fossil fuel production and use systems with natural sinks	• Collaborate with the USFS in tests to evaluate the addition of coal combustion by-products in deep-mulching to enhance growth on marginal soils • Promote partnerships between coal suppliers, coal users, and others to fully realize the potential terrestrial carbon sequestration	• Seek and implement additional projects on innovative concepts for terrestrial sequestration • Conduct engineering-scale/field testing of projects that incorporate integration of forestry/soils/land-use sequestration and power generation
Advanced Concepts	Develop novel chemical reaction pathways and non-photosynthetic biological systems that enable carbon dioxide to be converted to useful products or chemical species that are more easily stored	• Research on a bio-scrubber that removes CO_2 and determination of the microbiological role in GHG sequestration • Studies on processes to convert CO_2 to fuels and chemicals	• Continue to seek and implement path-breaking concepts that have the potential to sharply reduce the energy required to convert GHG to useful products or forms amenable for sequestration
Modeling and Assessments	Assess the cost, risks, and potential of carbon sequestration technologies in a systems context Provide tools to enable the strategic selection of the most promising R&D activities	• Systems and engineering analysis of oxygen-enriched combustion with CO_2 recycle • Adapt oil & gas reservoir models to coal seams and saline reservoirs • Model sequestration potential of geological storage sites	• Assess retrofit applications of O_2-enriched combustion concepts • Construct appropriate models to assess the risk of geological sequestration, such as failure mode analysis and long-term performance and verification techniques • Develop sequestration guidelines integrated with monitoring methods to ensure environmental conformity and facilitate public acceptance • Evaluate advanced GHG sequestration and utilization concepts by developing modeling and assessment capabilities that compare the sequestration potential of concepts on the same basis and calculate the amount of carbon emissions avoided at net costs

For the PCAST report, Federal Energy Research and Development for the Challenges of the Twenty-First Century, visit the PCAST web site at:

http://www.whitehouse.gov/WH/EOP/OSTP/Energy/

For the joint DOE Office of Fossil Energy and Office of Science report, Carbon Sequestration: State of the Science, and for more information on the Carbon Sequestration Program, please visit our web sites:

- DOE Office of Fossil Energy @ http://www.fe.doe.gov
- DOE Federal Energy Technology Center @ http://www.fetc.doe.gov

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