CO_2 CAPTURE AND STORAGE IN GEOLOGIC FORMATIONS

A white paper prepared for the National Climate Change Technology Initiative

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EXECUTIVE SUMMARY

On June 11, 2001 President Bush directed the Secretaries of Energy and Commerce, along with the Administrator of the EPA, to develop a National Climate Change Technology Initiative (NCCTI). The NCCTI will develop innovative approaches in accordance with several basic principles, as outlined by the President. The approaches will be (1) consistent with the long-term goal of stabilizing greenhouse gas concentrations in the atmosphere; (2) measured, as we learn more from science, and build on it; (3) flexible to adjust to new information and take advantage of new technology; (4) ensure continued economic growth and prosperity; and, (5) pursue market-based incentives and spur technological innovation.

Carbon Sequestration

- A third option for global climate change
- Enables continued use of domestic energy resources and infrastructure
- Geologic formations have potential for essentially unlimited storage capacity
- Demonstrated industry interest, participation, and cost-sharing in public/private partnerships

"We all believe technology offers great promise to significantly reduce [greenhouse gas] emissions -- especially carbon capture, storage and sequestration technologies."

President George W. Bush
June 11, 2001

This report, *CO_2 Capture and Storage in Geologic Formations*, is one of eight energy-related white papers produced in response to the guidance for the NCCTI white paper. This white paper covers the capture of carbon dioxide (CO_2) from current and planned fossil energy systems and its *direct* sequestration in geologic structures. *Indirect* sequestration, the enhanced uptake and storage of CO_2 in soils, vegetation, and the oceans, along with direct injection of CO_2 into oceans, is covered in other white papers.

BACKGROUND

The United States Department of Energy has established an international leadership role in sequestration science and technology development through the Carbon Sequestration R&D Program. The Program is managed by the Office of Fossil Energy and implemented by the National Energy Technology Laboratory. R&D management is strongly focused on public-private partnerships with industry, academia, state and local governments, and international entities.

VISION, GOALS, AND BENEFITS

The Carbon Sequestration Program has conducted analyses to quantify the benefits that the United States could realize from an investment in carbon sequestration research and development. The program developed a "Pathway to Stabilization" scenario in which the *growth* in greenhouse gas emissions is slowed in the near-term and stopped by 2020. By working with market growth and natural capital-stock turnover, such a strategy allows time for new technology and low-cost options. It also prevents a rapid increase in GHG emissions over the next 20 years, thus minimizing the need for steep, economically disruptive reductions in the future.

In the near-term, value-added sequestration applications will provide a cost-effective means of reducing emissions and provide collateral benefits in terms of increased domestic production of oil and gas. In the mid- and long-term, advanced CO_2 capture technology and integrated CO_2 capture, storage, and conversion systems will provide cost-effective options for deep reductions in GHG emissions.

RESEARCH AND RELATED ACTIVITIES

The overarching goals of carbon capture and geologic storage research are to: (1) lower the cost of CO_2 capture; and, (2) ensure that CO_2 storage in geologic formations is safe and environmentally secure. Three areas of research have been identified: CO_2 separation and capture; CO_2 storage in geologic formations; and novel sequestration systems.

Public-private partnerships and cost-shared R&D are a critical part of technology development for carbon sequestration. Partnerships with industry are forged primarily through competitive solicitations. In FY 2000/2001, the DOE Carbon Sequestration Program published a solicitation and selected twenty cost-shared R&D projects in the areas of CO_2 capture and storage in geologic formations. The awards were selected from a pool of 124 proposals. This research has a 60 percent non-DOE cost-share.

Recognizing that the needs for new science and technologies to reduce greenhouse gas emissions is a global concern, the Carbon Sequestration Program is deeply engaged in building international partnerships throughout the world. These partnerships take various forms, including science and technology information exchanges, formal coordinated funding of research in the U.S. with research funded by industry and foreign governments, and cooperative research at sites both within and outside the U.S. As global interest and funding of carbon sequestration research grows, these collaborations will expand.

RECOMMENDATIONS: RD&D INITIATIVES

A coordinated set of Research Development and Demonstration (RD&D) partnership initiatives has been developed with the goal of responding to the five basic principles for the NCCTI as outlined by the President. By providing the science and technology base to support the implementation of a set of performance-related, market-based incentives, these initiatives will create the flexibility to take advantage of new technology and help ensure continued economic growth and prosperity, while increasing the options available for measured policy actions in the future through cutting-edge technologies. All the initiatives would be public-private partnerships.

The proposed RD&D initiatives address scientific advancements, technology development, and demonstrations, as well as the need for public acceptance of the results of the research. The first initiative, Regional Carbon Sequestration Network, particularly addresses the need for increased public awareness and outreach.

Regional Carbon Sequestration Network Regional challenges with regional solutions are the rationale for establishing a multi-site *regional carbon sequestration (RCS) network.* The purpose of the RCS network is to establish regional public-private partnerships to facilitate science and technology development and public outreach appropriate to each major sequestration region.

The diversity of GHG emission sources and possible geologic sequestration approaches in the U.S. would require from five to seven RCS region-specific demonstrations, or nearly $500 million for the duration of the RCS network. Each regional effort would be a cost-shared partnership between regional public and regional industrial entities, with the expectation that they would become self-sustaining by the tenth year.

Assuring the Viability of Carbon Capture and Sequestration Deployment of large-scale carbon dioxide (CO_2) capture and sequestration technologies requires substantially reducing the costs of CO_2 separation and capture and verifying the environmental efficacy of sequestration in geologic reservoirs. A phased approach to assuring the viability of large-scale carbon capture and sequestration is proposed.

In Phase I, Flexible Carbon Dioxide Capture and Separation Test Facilities necessary to facilitate and accelerate development of technologies to reduce CO_2 emissions are implemented through cost-shared, public-private partnerships including consortia of universities, industry (including technology developers and users), and governments dedicated to surmounting technical and economic barriers. Currently, there is a lack of adequate test capabilities in the U.S. The total cost of this initiative would be $250 million over 10 years.

Phase II would fund a series of "first-of-a-kind " Integrated Capture and Storage Pioneer Projects consisting of CO_2 capture, transport (as needed), storage, and independent monitoring and verification of the amounts stored. The initiative is envisioned as a 15-year program of cost-shared, commercial scale projects. Funding would be $1 billion Federal funds with a minimum of $1 billion matching funds from non-Federal sources. Testing capture and sequestration at this scale would provide the high quality science critical to build confidence for eventual commercial deployment of large-scale CO_2 capture and sequestration.

Enhanced Science and Technology for Geologic Storage The scientific knowledgebase and technologies for the less well-researched types of geologic storage need to be better defined. While some of the topics are currently being addressed in the Sequestration R&D Program, the depth and pace of the research is not consistent with the goals of achieving a robust science and technology pathway to stabilization. This initiative would increase both the scope and pace of research in these areas. The budget for this initiative is estimated at $10 million per year for the first five years to reach proof of concept and $20 million per year for five years of field projects, for a total of $150 million over 10 years.

Science and Technology for Novel Sequestration Systems This initiative addresses the longer-term needs for revolutionary science and new technologies which can combine energy production with the reuse and conversion of CO_2 as an alternative to emitting CO_2 to the atmosphere. It encompasses science and technologies to address small-scale sources, such as distributed energy systems, as well as larger-scale sources. This is the longest-term, highest-risk portion of the Carbon Sequestration Program portfolio. It has a time horizon of up to 30 years. Hence, it is reasonable to assume that there is little incentive for private sector investments in this area in the near-term. This would be a 10-year program of $150-200 million, with the first 5 years of exploratory science and technology funded at $10 million per year. The second 5 year phase would fund proof-of-concept testing of those few concepts identified in the first phase as most promising.

CO_2 CAPTURE AND STORAGE IN GEOLOGIC FORMATIONS

I. INTRODUCTION

Carbon Sequestration

- A third option for global climate change
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- Geologic formations have potential for essentially unlimited storage capacity
- Demonstrated industry interest, participation, and cost-sharing in public/private partnerships

"We all believe technology offers great promise to significantly reduce [greenhouse gas] emissions -- especially carbon capture, storage and sequestration technologies."

President George W. Bush
June 11, 2001

The United States seeks technology solutions to the challenge of global climate change. Toward that end, on June 11, 2001 President Bush directed the Secretaries of Energy and Commerce, along with the Administrator of the EPA, to develop a National Climate Change Technology Initiative (NCCTI). The NCCTI will develop innovative approaches in accordance with several basic principles, as outlined by the President. The approaches will be (1) consistent with the long-term goal of stabilizing greenhouse gas concentrations in the atmosphere; (2) measured, as we learn more from science, and build on it; (3) flexible to adjust to new information and take advantage of new technology; (4) ensure continued economic growth and prosperity; and (5) pursue market-based incentives and spur technological innovation. This report, CO_2 Capture and Storage in Geologic Formations, is one of eight energy-related white papers produced in response to the guidance for the NCCTI white papers. It has two objectives.

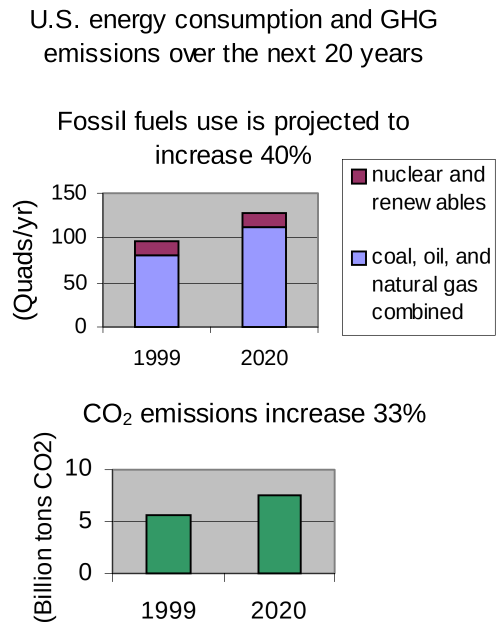
- ♦ Describe current activities in the area of CO_2 capture and storage in geologic formations and assess the level of greenhouse gas (GHG) emissions reduction that successful efforts could provide.
- ♦ Envision new RD&D initiatives that could accelerate technology development and expand the options for GHG emissions reduction at acceptable cost.

In developing this white paper the authors engaged, as expert reviewers, a group of professionals from industry, academia, and the national laboratories with expertise pertinent to the task of CO_2 capture and storage. These individuals reviewed draft documents and provided additions and changes. This process has provided a collaborative, state-of-the-art assessment of the CO_2 capture and geologic storage options for GHG emissions reduction – both those within reach in the near-term and those possible in the longer-term with an increased commitment to science and technology development.

This white paper covers the capture of CO_2 from current and planned fossil energy systems and its *direct* sequestration in geologic structures. *Indirect* sequestration, the enhanced uptake and storage of CO_2 in soils, vegetation, and the oceans, along with direct injection of CO_2 into oceans, is covered in other white papers.

II. BACKGROUND

Low-cost, reliable energy is one of the foundations of the United States economy. In 1999, the United States consumed 3 kilowatt-hours of energy for each dollar of economic activity, and 85% of that energy came from fossil resources: coal, oil, and natural gas. Continued reliance on fossil fuels is forecast well into the future. The Energy Information Administration within the U.S. Department of Energy (DOE) projects U.S. consumption of coal, oil, and natural gas to increase by 40% over the next 20 years. Greenhouse gas emissions are projected to rise 33% over that same time period, based on a modest shift from coal to natural gas.[1]



Source: EIA Annual Energy Outlook 2001

A. ATMOSPHERIC STABILIZATION

In 1992 the United States and 160 other countries ratified the Rio Treaty, committing to:

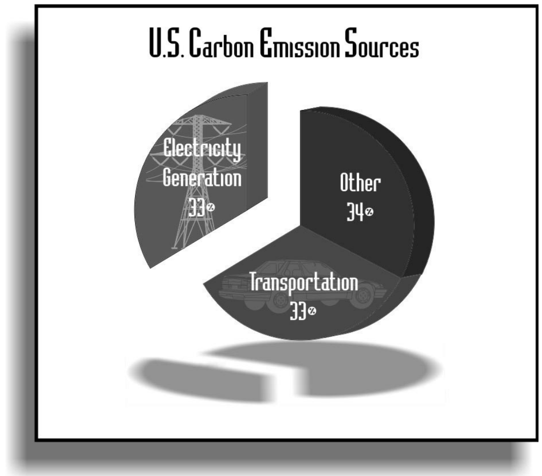
> *Stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.*

Today the atmosphere contains 30% more greenhouse gases than it did prior to the industrial revolution[2], and the concentration is increasing steadily at a rate of 1-2 ppm per year.[3] CO_2 is the primary greenhouse gas representing roughly 83% of anthropogenic effect.[4]

The challenge of global climate change is to decouple GHG emissions and the use of low-cost, reliable energy resources. Two options have generally been considered for this. The first is to conserve energy and to use it more efficiently. The second is to switch to renewables, nuclear power, and low-carbon fuels such as hydrogen or natural gas.

A third option is carbon sequestration, which removes CO_2 from energy systems and stores it. There has been a large body of work conducted over the past decade on carbon sequestration. This paper builds on those previous efforts.[5,6,7,8,10]

B. CARBON SEQUESTRATION: PATHWAY TO STABILIZATION



The U.S. DOE has established an international leadership role in the sequestration technology development through the Carbon Sequestration R&D Program. The Program is managed by the Office of Fossil Energy and implemented by the National Energy Technology Laboratory. R&D management is strongly focused on public-private partnerships with industry, academia, state and local governments, and international entities. The current Carbon Sequestration Program includes the capture and geologic storage activities that are discussed in Section IV of this white paper, as well as science-based efforts in ocean and terrestrial sequestration that are identified in other white papers.

The goals of the current program address a major first step toward a "Pathway to Stabilization." One goal is to develop technology which can be deployed by 2015, and thereby reduce the projected level of emissions in 2020 to the levels projected for 2010 by the Energy Information Administration in its Annual Energy Outlook.

The science and technology RD&D initiatives identified in Section V of this white paper support the goal of the current program *as well as* the longer-term goal of atmospheric stabilization through capture and storage technology that can be applied to many CO_2 sources.

Carbon Sequestration: Pathway to Stabilization

- Public-private partnerships: Industry and international collaboration with 60% non-federal cost-sharing in current work.
- Technology demonstrations: Existing and planned projects to validate approaches, costs, and effectiveness.
- Fundamental and exploratory research: Novel sequestration concepts for low-cost, broadly applicable systems.
- Stabilization: 2015 emissions-reduction targets are a critical first step to longer-term atmospheric stabilization.

III. Vision, Goals, and Benefits

The vision of carbon capture and geologic storage is to reduce the climate change impacts of fossil fuel conversion and use. Over the longer term, the goal is to achieve this at an incremental cost of $10 per ton net of carbon emissions avoided. A large part of the effort over the next ten years will be to field test storage concepts, with the goal of verifying their safety and environmental acceptability and assuring public acceptance of carbon sequestration.

Carbon Sequestration Vision

- Reductions in GHG emissions that increase the cost of energy services by 5% or less
- Safe and environmentally acceptable CO_2 storage – with capacity to store many decades worth of emissions
- Sequestration options with significant collateral benefits in terms of enhanced resource recovery.

A key aspect of the program is to develop the data, information and techniques necessary to (1) assure the safe, essentially permanent storage of CO_2 and (2) verify the actual amounts of CO_2 sequestered. Both of these aspects are critical to developing market-based sequestration options. For example, proven and accepted monitoring and verification protocols are necessary components of sequestration systems. This serves three critical purposes: (1) providing assurance of the amounts of CO_2 that can be considered permanently sequestered, (2) supporting public acceptance of the safety and environmental security of sequestration, and (3) providing a consistent basis to measure and account for volumes of CO_2 sequestered for the application of potential incentives.

When considering the vision of carbon sequestration R&D, it is important to place it in the context of the overall environmental impacts of fossil fuel utilization over the last 30 years. Over that time, emissions of sulfur, particulate matter, and nitrous oxides have been reduced dramatically. Further improvements are on the horizon. Coal and other heavy hydrocarbon gasification, fuel cells, hybrid electric power systems, and other new technologies will enable fossil fuels to be utilized with near-zero environmental impact. Evolving toward elimination of the impact of fossil fuel use on the global climate is a natural progression.

The Carbon Sequestration Program has conducted analyses to quantify the benefits that the United States could realize from an investment in carbon sequestration research and development.[8] The program developed a "Pathway to Stabilization" scenario in which the *growth* in GHG emissions is slowed in the near-term and stopped by 2020. By working with market growth and natural capital stock turnover, such a strategy allows time for new technology and low-cost options. It also prevents a rapid increase in GHG emissions over the next 20 years thus reducing any need for steep, economically disruptive reductions in the future.

Figure 1 shows U.S. GHG emissions over the next 50 years under the Pathway to Stabilization scenario. The middle line is the reference case projection from the Energy Information Administration's Annual Energy Outlook 2002, extrapolated to 2050 and is shown for comparison. The reference case is fairly aggressive with respect to technology development and assumes a decrease in carbon intensity of one percent per year. The top line is a "2000 technology freeze" scenario in which the efficiency of energy production and use technology does not improve beyond that of current technology.

FIGURE 1. GREENHOUSE GAS EMISSIONS SCENARIOS FOR THE UNITED STATES

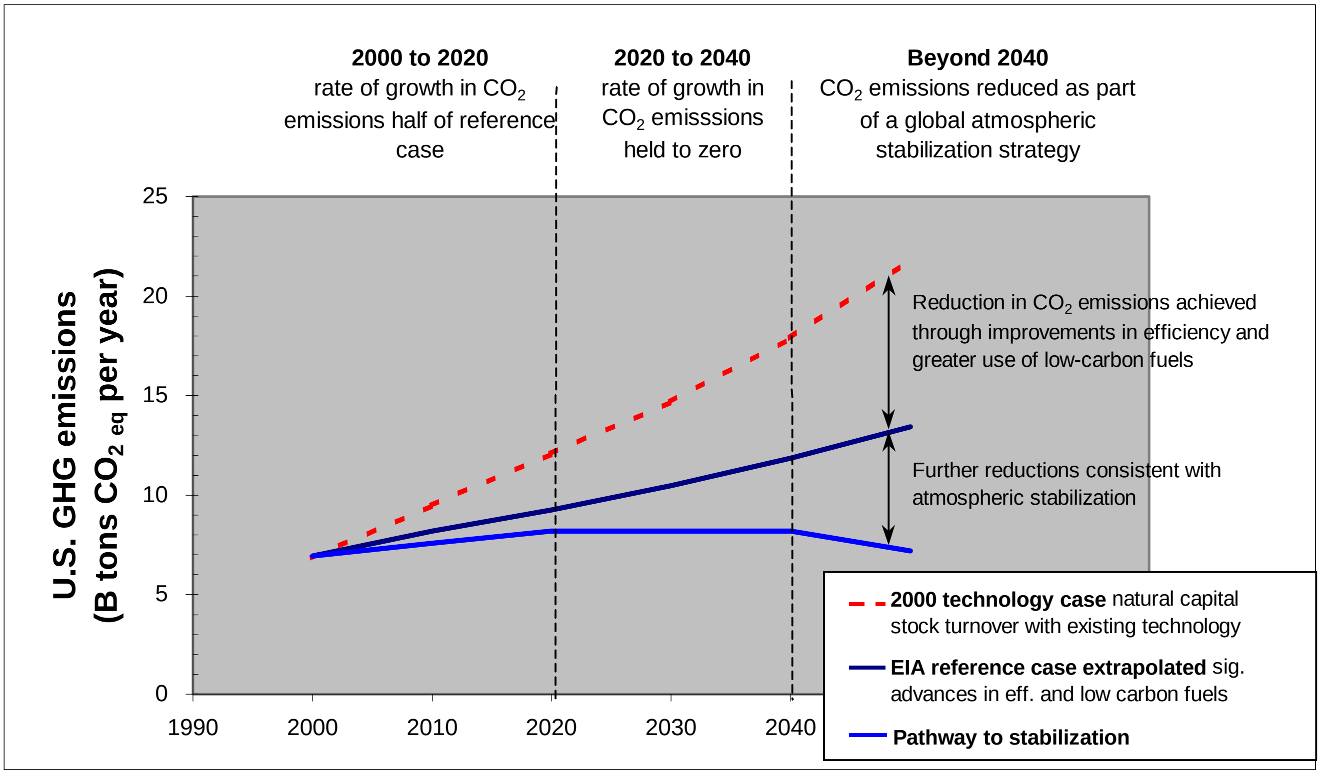


Figure 1 shows that over time a large gap evolves between the reference case scenario and the Pathway to Stabilization. Technology development and market-based incentives for the three major options (increased efficiency, low- and zero-carbon energy sources, and sequestration) can together achieve the needed emissions reduction. The CO_2 capture and geologic sequestration option has the potential to contribute significantly. Roughly one third of all U.S. greenhouse gas emissions come from large point sources that are amenable to capture[9] and the capacity of domestic geologic formations is large enough to store many centuries worth of CO_2 emissions (see Table 1).

The capacity estimates shown in Table 1 are likely conservative as the CO_2 sequestration potential in geologic reservoirs depends on a variety of poorly defined factors. These include reservoir volume, porosity, permeability, and pressure. Because these factors vary widely even within the same reservoir, it is difficult to precisely define these properties and determine a reservoir's storage potential with certainty. For example, the storage potential in saline reservoirs has been estimated to range from 5-500 Giga Tons (Gt) of CO_2 in the U.S. and 320 to 10,000 Gt globally. However,

TABLE 1. CO_2 STORAGE CAPACITIES OF DOMESTIC GEOLOGIC FORMATIONS

GEOLOGIC RESERVOIR	ESTIMATED CO_2 STORAGE CAPACITY (BILLIONS OF TONS CO_2)
Unmineable Coal Beds	15-20
Depleting Oil Reservoirs	40-50
Depleting Gas Reservoirs	80-100
Saline Formations	5-500
High Organic Shales	TBD
TOTAL	140-670

Source: ARI; Winter and Bergman, Energy Conversion Management, Vol. 34, 1993 more detailed analysis of the Mt. Simon Sandstone reservoir in the Midwestern U.S. by Battelle indicates that the storage capacity in this formation alone may range from 115 to 655 Gt.

Over the next 20-30 years, "value added" sequestration applications (those which both reduce greenhouse gas emissions and result in the additional production of hydrocarbons) can provide a cost-effective means for reducing emissions, and provide collateral benefits in terms of increased domestic production of oil and natural gas. In the mid- and long-term, even more advanced CO_2 capture technology and integrated CO_2 capture, storage, and conversion systems can provide cost-effective options for deep reductions in GHG emissions.

National Benefits of Carbon Sequestration in Depleting Oil Reservoirs and Unmineable Coal Beds

The Carbon Sequestration Program contracted Advanced Resources International (ARI) to assess the carbon sequestration capacity of the depleted oil reservoirs and unmineable coal seams in the United States. ARI's assessment is based on the sites most amenable to CO_2 storage and resource recovery and recognizes limitations on the rate at which CO_2 can be injected and product recovered. Assuming a fully funded R&D effort and modest market-based incentives, ARI estimates that **by 2020 CO_2 could be stored in depleting oil reservoirs and unmineable coal seams at a rate of 400 million tons per year.**

By 2020, such applications would provide the following collateral benefits:

- 365 million barrels of oil per year additional domestic oil production
- 730 billion cubic feet per year of additional domestic natural gas production
- $12 billion per year improvement in the trade balance by displacement of imported crude oil and natural gas

IV. Research and Related Activities

The overarching goals of carbon capture and geologic storage research are 1) to lower the cost of CO_2 capture and storage, and 2) to ensure that CO_2 storage in geologic formations is safe and environmentally secure. Three areas of research have been identified. They are:

- CO_2 separation and capture,
- CO_2 storage in geologic formations, and
- Novel sequestration systems.

Each research area is discussed in detail below. Technology Profiles of the three areas are presented in Appendix A. Also discussed here are two cross-cutting drivers of high importance to the CO_2 capture and geologic storage effort: public-private partnerships and international collaboration.

A. Public-Private Partnerships and Cost-Shared R&D

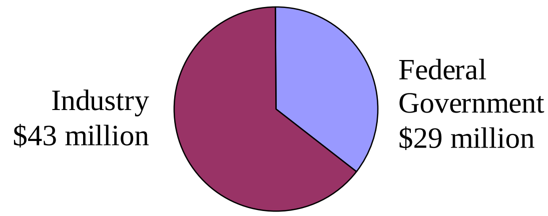
Public-private partnerships and cost-shared R&D are a critical part of technology development for carbon sequestration. These relationships draw on pertinent capabilities that the petroleum and chemical industries have built up over decades, important knowledge and capabilities of the National Laboratories, the U.S. Geological Survey, and academia, and collaborative efforts for the identification and selection of promising research pathways. Through partnerships the program has been able to harness these capabilities and direct them to the goal of carbon sequestration technology development.

The program conducts outreach to raise awareness of carbon sequestration activities among industry professionals, and also to gather ideas and opinions about appropriate directions for technology development. In May 2001, the National Energy Technology Laboratory sponsored the First National Conference on Carbon Sequestration. Over 150 technical papers were presented at the conference on a wide variety of topics related to carbon sequestration, and over 400 persons attended. The Carbon Sequestration Program maintains an up-to-date webpage on the NETL site and sends out a monthly email-based newsletter to over 500 subscribers.

Partnerships with industry are forged primarily through competitive solicitations. In FY 2000/2001, the Carbon Sequestration Program published a solicitation and selected twelve cost-shared R&D projects in the areas of CO_2 capture and storage in geologic formations. The awards were selected from a pool of 124 proposals. The competitive solicitation process compels companies to offer significant cost-share and also brings forward the companies and researchers with the best ideas and strongest capabilities. The program achieved an average non-DOE cost share of 60% from the solicitation. This is significantly higher than the program overall cost share of 40% (already quite high for early stages of technology development), indicating the strong potential associated with the value-added storage concepts. A list of the awards is contained in Section VII, Supporting Information.

Advances in the development of carbon sequestration technologies are greatly enhanced through research partnerships with colleges and universities, private research institutes, national laboratories, and other federal and state agencies. Competitive solicitations are directed towards these institutions to spawn innovative, breakthrough concepts to mitigate GHG emissions from fossil fuel energy systems. About one-fourth of the FE funding for carbon sequestration is allocated to university-led research efforts, while universities participate in over one-half of the projects in the research portfolio.

The National Energy Technology Laboratory designated a research focus area for carbon sequestration science (CSS) to conduct science-based research and analysis in areas related to carbon sequestration using in-house facilities and resources. The CSS group conducts a broad portfolio of sequestration research projects, partnering with academic institutions, private industry, and other national laboratories and agencies.



B. International Collaboration

Recognizing that the needs for new science and technologies to reduce greenhouse gas emissions is a global concern, the Carbon Sequestration Program is deeply engaged in building partnerships throughout the world. These international partnerships take various forms including science and technology information exchanges, formal coordinated funding of research in the U.S. with research funded by industry and foreign governments and cooperative research at sites both within and outside the U.S. As global interest and funding of carbon sequestration research grows, these collaborations will expand.

These international collaborations are conducted 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. Foremost among these multilateral agreements is the International Energy Agency's Greenhouse Gas Research and Development Programme (IEA/GHG), which is funded by 17 member countries plus the European Commission and seven private sector sponsors. In addition, member country participation is supported by "in-country" industrial consortia in many cases. The IEA/GHG conducts technology assessments of existing, new, and emerging advanced technologies. Equally important, it stimulates and facilitates practical R&D cooperative activities among member countries and industry. For complete information refer to http://www.ieagreen.org.uk/.

Some of the IEA/GHG facilitated activities are described later in this paper. Other examples of multilateral and bilateral public-private partnerships specifically discussed in later sections include the following,

- The CO_2 Capture Project in collaboration with the European Commission, the Klimatek Program of Norway, and nine major international energy companies.

- The Dakota Gasification/Weyburn project to develop CO_2 monitoring and verification techniques for use in depleting oil reservoirs, in collaboration with provincial and national governments in Canada, the European Commission, and industry.

- The natural analogs research (natural CO_2 reservoirs) being conducted by Advanced Resources International, of the U.S. in cooperation with researchers from around the world, (funded by the European Commission), Australia, and worldwide industry.

- The oxyfuel combustion feasibility testing and proof-of-concept testing program in Canada, led by Natural Resources Canada, a consortium of international companies, and partially funded by a broad spectrum of non-Canadian government and private funding entities.

These are but a few of the most prominent examples. Other important collaborations are underway with the European Commission, Australia, Canada, and Japan.

C. CO_2 Separation and Capture

Roughly one third of the United States' anthropogenic CO_2 emissions come from large fossil fuel conversion systems, mostly air-fired combustion. Because air is 79% nitrogen, air combustion effluent contains CO_2 in dilute concentration (3-12% by volume). Concentrated CO_2 (greater than 90%) is needed for most storage, conversion, or reuse applications to be economic. Sequestration R&D seeks to develop capture systems that produce a highly pure, pressurized stream of CO_2 at relatively low cost. Generally, three technology paths are being explored; post combustion, oxygen-fired combustion, and pre-combustion capture.

Given the enormous infrastructure of combustion-based power-generation assets in the United States, developing technologies to capture CO_2 from flue gas (post-combustion capture) is a major thrust and a wide range of options are being pursued. The current technology for CO_2 capture is a class of chemical absorbents called amines. Amines are used to remove CO_2 from natural gas and also to produce by-product food-grade CO_2 from power plants and other industrial processes. However, the cost is on the order of $50 per ton of CO_2, and is too high for cost-effective GHG emissions reduction. Further, current CO_2 capture systems require substantial energy and can reduce a power plant's net generation rate by as much as 30%.

-- Public-Private Partnership --

CO_2 Capture Project

On July 13, 2001 President Bush announced that the U.S. DOE had signed an agreement with an international team of energy companies for the CO_2 Capture Project (CCP), to develop a new set of technologies for reducing the cost of capturing CO_2 from fossil fuel combustion plants. The CCP is led by BP and includes Shell, Chevron/Texaco, Pan Canadian (Canada), SunCoe Energy (Canada), ENI (Italy), Statoil Forskingssenter (Norway), and Norsk Hydro (Norway). The goal of the CCP is to lower the cost of CO_2 capture and storage 50% in retrofit applications and 75% in new build applications. The CCP plans to be in the 'proof of concept' stage by 2003/2004 and achieve at least one large-scale application by 2010. The government/industry partnership is for three years and has a total cost of $13.8 million. The CCP is providing 64% cost share.

For more information, visit the CCP website at www.co2captureproject.org

The Program is exploring a portfolio of new technologies to reduce the capital and energy penalty costs for post combustion capture. Technologies under development include regenerable sorbents, advanced membranes, and novel concepts such as forming CO_2 hydrates to facilitate capture. The hydrate process, for example, could be especially attractive for advanced coal conversion systems like coal gasification combined cycle systems.

A challenge for post-combustion capture is the enormous amount of gas that must be processed per unit of CO_2 captured. This is especially true for natural gas combustion turbines where the concentration of CO_2 in the flue gas can be as low as 3%. The CO_2 gas must be absorbed into a liquid via contact, and then the resulting mixture separated. Novel gas/liquid contactors are being explored. A breakthrough in contactor technology could enable amines as well as physical absorbents such as methanol to be more cost-effective.

Another approach being researched for capturing CO_2 from existing power plants is oxygen-fired combustion, burning with pure oxygen or oxygen-enriched air. Not only is the CO_2 in the flue gas more concentrated, but the volume of combustion gas is reduced by as much as 80%, significantly lowering the capital cost of both the boiler and down-stream control equipment. To compensate for the increased heat when fossil fuels are combusted in oxygen, CO_2 is recycled to maintain furnace temperatures at levels suitable for boiler surfaces. Hence, oxygen-fired combustion is sometimes known as "CO_2 recycle" combustion.

For new construction or re-powering of existing coal-fired power plants, there are some technology options available that can provide a pure stream of CO_2 at very low incremental cost. These processes are referred to as pre-combustion decarbonization, which leads to making concentrated streams of hydrogen (H_2) and CO_2 in steam reforming of natural gas and gasification of heavy hydrocarbons. In gasification, the hydrocarbon is heated, causing it to break up into H_2, carbon monoxide (CO) and CO_2, and some methane and other light hydrocarbons. It is easy enough to react the CO with water (H_2O) to form H_2 and CO_2. It is then convenient to separate the CO_2 and H_2. The H_2 can be used in a combustion turbine or fuel cell and the CO_2 sequestered. A strong benefit of gasification compared to oxygen combustion is that it gets a lot of the needed oxygen from steam, thereby reducing the costs of fossil fuel conversion and increasing the overall efficiency of the power plant. More efficient power plants emit less CO_2 per unit of energy produced.

The options for new energy conversion processes are exciting, but it is important to remember the United States' mammoth capital stock of air-fired combustion assets. A breakthrough in technology to retrofit/repower existing facilities would be extremely valuable to the U.S. economy as well as other developed and developing nations with significant coal resources.

D. CO_2 Storage in Geologic Formations

Depleting Oil Reservoirs and Unmineable Coal Seams

Of the various types of geologic formations, depleting oil reservoirs and unmineable coal beds have the highest near-term potential for storing CO_2. This is due to three reasons: (1) their large and geologically diverse storage capacity; (2) the presence of existing surface and downhole infrastructure; and, (3) the strong base of industrial experience with injecting CO_2 into depleting oil reservoirs to enhance recovery. In 2001, industry injected 30 million in tons of CO_2 for enhanced oil recovery, providing 180,000 barrels per day of additional domestic oil production.

However, using depleted oil reservoirs and unmineable coal seams for carbon sequestration has goals and requirements that are fundamentally different from using CO_2 for additional oil and gas recovery. Currently, industry's goals are to maximize oil and gas recovery using as little CO_2 as possible; geologic sequestration's goals are to maximize CO_2 injection. Current practices are to keep the injected CO_2 in the reservoir for only a handful of years; sequestration seeks to store the CO_2 for thousands of years.

— Public/Private Partnership —

CO_2 STORAGE IN DEPLETING OIL RESERVOIRS

The Sequestration Program is funding a cost-shared project to monitor injected CO_2 at the Weyburn field in Canada. PanCanadian Resources is injecting 96% pure CO_2 from the Dakota gasification facility in North Dakota into the Weyburn oil reservoir at a rate of 95 million cubic feet per day. The operator plans to employ seismic methods and geochemical sampling to evaluate the distribution of CO_2 in the reservoir and the chemical reactions that occur between the CO_2 and the reservoir rock and fluids. The total cost of the project is $26 million over 4 years, with industry (and other governments) providing 85% cost share.

Beyond these and other differences in objectives, there are areas where CO_2 sequestration and production of "value added" hydrocarbons are complementary and mutually beneficial. First, the additional production of the reservoir's oil and natural gas can help defray some of the costs of CO_2 injection and long-term storage. Also, advances in technology can expand the types and number of reservoirs amenable to CO_2 sequestration. In turn, the capture portion of the CO_2 sequestration program will help lower the costs and expand the volumes of CO_2 available for injection. Finally, it should be noted that the United States is the world leader in CO_2-enhanced production of oil and coal bed methane technology. Production incentives (in the form of Section 29 tax credits) for the application of this technology were a major contributor to attaining this leadership position.

The two overriding R&D areas for geological storage of CO_2 are: (1) developing reliable monitoring, verification and mitigation technology; and, (2) sponsoring appropriate health, safety and environmental (HSE) risk assessment data collection and methodology. Considerable emphasis is focused on modifying existing technology to reduce its costs and improve its use for monitoring geologic storage of CO_2. A significant effort is also underway to understand the interaction of injected CO_2 on the integrity of the reservoir's cap rock as well as the flow and storage properties of CO_2 in the reservoir. With reliable monitoring systems and improved risk assessment data, the Program is seeking to gain both the scientific community's and the public's confidence in this valuable CO_2 sequestration option.

— Public-Private Partnership —

CO_2 Storage in Unmineable Coal Beds

Consol Inc. is testing the storage of CO_2 in an unmineable coal seam in southwestern Virginia. Consol will use new directional drilling techniques designed to increase both coal bed methane (CBM) recovery and CO_2 storage capacity. The field experiment will be conducted on a 200 acre site and will involve CO_2 injections into a coal seam over a two and a half year period. Consol will quantify the amount of CO_2 that can be stored in the coal seam as well as the incremental CBM production. Consol will also monitor the concentration of CO_2 in ground water above and below the seam to verify the stability of CO_2 storage. The cost of this project will be $8.8 million over 7 years, with Consol providing 20% cost-share.

For depleting oil reservoirs, carbon sequestration research is focused on: (1) developing methods and technologies aimed at maximizing the amount of CO_2 that can be stored in a depleting oil reservoir while maintaining formation integrity; and, (2) verifying that the injected CO_2 remains safely in the reservoir for the long-term.

For unmineable coal seams, research is focused on understanding: (1) fundamental CO_2 adsorption mechanisms; (2) the effects of CO_2 injection on the permeability of the coal; and, (3) optimum mixtures of CO_2 and flue gas as injectants. Currently, the Program is supporting laboratory work, a series of reservoir simulations, and a field experiment of CO_2 sequestration in the San Juan Basin to better understand this process. A critical goal in both areas is to improve understanding of these storage processes so that modest incentives may make long-term CO_2 storage in oil reservoirs and coal seams a cost-effective option.

CO_2 Storage in Other Geologic Formations

The carbon sequestration program maintains an interest in all geologic formations that have the potential to store CO_2. Expanding the number of geologic options will provide sites in essentially all regions of the country and expand geologic storage capacity for CO_2. To better understand the variety of geologic storage options, Advanced Resources International and the University of Utah are conducting analyses of core samples from natural CO_2 reservoirs. These formations have held CO_2 over geologic time and researchers hope to determine the chemical reactions that have occurred and how they may have impacted their integrity and sealing capacity.

Saline formations. Saline formations are high porosity and permeability sediments that are filled with brackish, non-potable water. Many have a layer of low permeability rock above and thus could provide secure storage for CO_2. Hazardous waste is currently disposed in such saline formations. While there is no experience in the U.S. with injecting CO_2 into these formations, a large project is in operation in the North Sea off the coast of Norway. Since 1997, Statoil has been capturing roughly 1 million tons of CO_2 per year from a natural gas processing platform and injecting this into a saline formation below the ocean bottom. Working with the IEA Greenhouse Gas Programme, the U.S. DOE Program has supported efforts to monitor the flow and storage of the injected CO_2 in this formation.

Research is aimed at developing field practices to maximize CO_2 storage capacity while maintaining formation integrity. Other work is aimed at better understanding the dissolution reactions involving the CO_2 and other chemical species and minerals in the saline formation, with the objective of enhancing the permanence of CO_2 storage.

Depleting gas reservoirs. Formations that have held natural gas over geologic time also offer promise for secure CO_2 storage. In theory, CO_2 could be injected on one side of a depleted natural gas formation to create pressure to drive the remaining gas to producing wells. In practice, the injected CO_2 mixes with reservoirs natural gas, resulting in high costs for processing the contaminated natural gas. Sequestration research is focused on developing CO_2 injection practices that enable production of acceptably pure natural gas, as well as developing fully depleted gas reservoirs as storage repositories.

Hydrocarbon-bearing shale formations. Shale formations with high organic carbon content can store CO_2 much the same way as coal formations. In theory, CO_2 can be used to displace the methane that is adsorbed in organically-rich shale, with the CO_2 being adsorbed and thus securely stored. While the geologic opportunities are widespread, particularly in the Appalachia Basin, the concept of using organically-rich shales to store CO_2 has not been tested. Initial efforts in this area would involve acquiring core samples and testing their CO_2 absorption properties, followed by a series of progressively more rigorous field tests.

E. Novel Sequestration Systems

The longer-term timeframe of the program (post 2015) is focused on novel systems that can be applied to many CO_2 sources for storage or reuse in support of atmospheric stabilization. This research is in its infancy, and the program currently supports a modest effort in exploratory research and fundamental science.

Program activities include advanced GHG conversion and utilization schemes that either convert GHGs into useful products, or to benign materials that do not interact with the earth's climate. Also, research is underway on fossil fuel conversion systems that produce a highly concentrated stream of CO_2 suitable for sequestration. For example, one potential pathway is to mimic natural CO_2 conversion processes. Plants convert CO_2 to organic matter via photosynthesis, mollusks use CO_2 in ocean water to build their shells, and sandstone reacts with CO_2 in the air to form minerals. Evidence suggests that CO_2 trapped in geologic formations over eons has been converted to carbonates and other species, though the exact mechanisms are not understood. Elucidating and building on these natural biogeochemical processes may result in scientific breakthroughs for low-cost, safe, widely applicable sequestration systems.

V. Recommendations: RD&D Initiatives

A coordinated set of RD&D partnership initiatives has been developed with the goal of responding to the five basic principles for the NCCTI as outlined by the President. By providing the science and technology base to support the implementation of a set of performance-related, market-based incentives, these initiatives will create the flexibility to take advantage of new technology and help ensure continued economic growth and prosperity, while increasing the options available for measured policy actions in the future through cutting-edge technologies. All these initiatives would be public-private partnerships.

A key recommendation is that performance-related market incentives be implemented in parallel with these RD&D initiatives. The vision for the performance-related market incentives is that they would be similar to the Section 29 tax incentives, which along with public-private R&D partnerships have been extremely successful in bringing technologic innovation to natural gas supply. In this new situation, one can envision tax incentives that are based upon the quantity of CO_2 avoided through capture and storage. The rationale for early implementation of these incentives is to provide appropriate market signals to the private sector for both R&D investments and early deployment investments.

A key advantage to the coupling of RD&D initiatives with these market incentives is that such a combination can be assumed to increase the capability of industry to assume the funding responsibilities for the demonstration and deployment of novel and advanced systems in the longer term. The proposed longer-term Federal funding profiles for the Carbon Sequestration Program, including these initiatives reflect this assumption.

The proposed RD&D initiatives address scientific advancements and technology development, as well as the need for public acceptance of the results of the research. The first initiative in particular, the Regional Carbon Sequestration Network, addresses the need for increased public awareness and outreach.

A. Regional Carbon Sequestration Network

Regional challenges with regional solutions are the rationale for establishing a multi-site *regional carbon sequestration (RCS) network.* The purpose of the RCS network is to establish regional public-private partnerships to facilitate science and technology development and public outreach appropriate to each major sequestration region. This would include a focus on providing information to the public. The RCS network will involve academia, national laboratories, energy producers and users, and state and local agencies. The network would help provide region-specific scientific data and options to ensure the use of environmentally sound practices and the long-term safety of the sequestration alternatives being considered.

The benefits of a regional approach to carbon sequestration include:

- Increased reliance on university, industrial, and national laboratory partnerships for sequestration technology development,
- Application of regionally appropriate monitoring and diagnostic tools to predict, verify, and validate the safety and environmental efficacy of sequestration,

- Improved engagement of state and local officials in regions with significant opportunities for CO_2 capture and storage in geologic formations, and
- Assuring each region has a focal point for providing relevant information to the public.

The RCS network would also provide a platform for the United States to assist developing countries in their efforts to reduce GHG emissions through the use of carbon sequestration technologies. In situations where geologies or geographies are similar, scientists, engineers and policy makers from developing countries could visit a RCS network site, test their ideas through cost-shared agreements, and/or learn about monitoring, verification, and safety options.

Implementation of the RCS network should proceed in three phases of about two years each and include evaluation and selection of potential reservoirs, field tests, and verification and validation of sequestration approaches. Each RCS network field trial would require $100 million of Federal funding. The diversity of GHG emission sources and possible geologic sequestration approaches in the U.S. would require from five to seven RCS region-specific demonstrations, or approximately $500 million for the duration of the RCS network. Each regional effort would be a cost-shared partnership between regional public and regional industrial entities, with the expectation that they would become self-sustaining by the end of the tenth year.

B. Assuring the Viability of Carbon Capture and Sequestration

Phase I. Flexible Test Facilities for CO_2 Capture

Separating and capturing CO_2 emissions from large point sources such as power plants accounts up to 80% of the estimated costs of carbon sequestration. It is widely accepted that these costs, including capital and energy penalty, could be significantly reduced through focused R&D efforts. An essential sequence in the technology development pathway is testing and evaluation at a large enough scale to overcome technical and economic barriers associated with CO_2 capture. Also, because of the variety of process streams containing high concentrations of CO_2, multiple technical approaches to CO_2 concentration and removal will be necessary.

Several flexible CO_2 capture and separation facilities are necessary to adequately test and accelerate development of technologies to reduce CO_2 emissions, especially those produced by the energy sector, to the point of commercialization. Currently, there is a lack of adequate such test capabilities in the U.S.

Facilitation and implementation of these test facilities would be through cost-shared, public-private partnerships including consortia of universities, industry (including technology developers and users), and governments dedicated to surmounting technical and economic barriers. Federal funding of $15 to $25 million would be required for startup of each flexible test facility, and $5 million per year through 2010 for parametric testing of promising CO_2 separation and capture approaches, including those applicable to existing conversion systems and advanced technologies such as gasification. The total cost of this initiative would be $250 M over 10 years.

Phase II. Integrated Capture and Storage Pioneer Projects

Most of the capture facilities in use today process from 100 to 300 tons of CO_2 per day. By comparison, a large industrial source can generate more than 22,000 tons of CO_2 per day. Also, to adequately verify large-scale sequestration, field tests consisting of injecting at least 1,000,000 tons of CO_2 per year (for 10 years) into representative and realistic geologic sites are needed. Testing capture and sequestration at this scale would provide the high quality science critical to build confidence for eventual commercial deployment of large-scale CO_2 capture and sequestration.

Phase II would fund a series of "first-of-a-kind" integrated projects consisting of CO_2 capture, transport (as needed), storage, and independent monitoring and verification of the amounts stored. This would be a 15 year program of cost-shared, commercial scale projects. Funding would be $1 billion Federal funds with a minimum of $1 billion matching funds from non-Federal sources. A separate appropriation with advance appropriations of $100M average over the first 10 years is envisioned as part of a combined authorization and appropriation action.

As envisioned, several rounds of competitive solicitations would be conducted for projects that have specific capture and storage sites, plus independent monitoring and verification programs. Non-governmental organizations, including international groups, would be invited to serve on advisory boards, ensuring the transparency of results. Project sponsors would have to demonstrate they have financing available and committed. Project-specific/supporting R&D or testing would be eligible, however projects with the best demonstrated "technical readiness" would be favored. Similarly, projects offering the lowest cost per ton of CO_2 avoided would be favored.

Both geographic and technology-specific diversity would be addressed in Phase II, developing confirmed regional capability and capacity in the project selections. Examples of such criteria include:

- Capture projects from different kinds of energy or industrial facilities, including power generation, natural gas processing, refineries, ethanol production, fertilizer and cement plants, as well as other large point sources would be eligible. Large-scale capture facilities must have provisions to test, at appropriate scale, advanced capture technologies under development in other programs.

- Storage in depleting oil reservoirs with diverse geologic parameters (formation and host rock properties) and geographic locations (West, Southwest, Northern Slope, Mid-Continent). Up to 12 different storage settings are envisioned to achieve program goals.

- Storage in different types of deep unmineable coal seams representative of the geographic and geologic diversity of the 10 major U.S. coal basins.

- Storage in deep saline formations and other geologic formations, as described elsewhere in this paper, would be eligible for inclusion as the R&D described elsewhere in this paper progresses the science and technology to the necessary state of "technology readiness."

C. Enhanced Science and Technology for Geologic Storage

The scientific knowledge and technology development needs are poorly known for the less well-researched options of geologic storage. While these are currently being addressed in the Carbon Sequestration R&D Program, the scope and pace of the research is not consistent with the goals of achieving a science and technology base for achieving stabilization. This initiative would increase both the scope and pace of research in these areas.

Establishing the feasibility of CO_2 storage in organically rich shales and depleted or near-depleted natural gas fields and saline formations would greatly expand the available CO_2 storage capacity and regional diversity of available capacity. The first step would be to rigorously define the size, characteristics, and location of these new geologic settings that may be amenable to long-term CO_2 storage. The next step would be to conduct laboratory and reservoir modeling studies to understand the science and physics that will control the injection flow and permanence of CO_2 in these formations. Third is a series of small field pilots that would establish the "proof of concept." With this base of science and field-based proof, the final step would be a series of large scale field projects, one in each of the several geologic settings, to optimize technology and accelerate the acceptance of these storage options by industry.

The budget for this initiative is estimated at $10 million per year for the first five years to reach proof of concept and $20 million a year for five years of field projects, for a total of $150 million over 10 years.

D. Science and Technology for Novel Sequestration Systems

This initiative addresses the longer-term needs for revolutionary new technologies which can combine energy production and conversion with the reuse and conversion of CO_2 as an alternative to emitting CO_2 to the atmosphere. It encompasses science and technologies to address small-scale sources, such as distributed energy systems as well as larger-scale. This is the longest-term, highest-risk portion of the Carbon Sequestration Program portfolio. It has a time horizon of up-to-30 years. Hence, it is reasonable to assume that there is little incentive for private sector investments in this area in the near-term.

Moreover, since it will require significant advances and discoveries in science, before technology can be developed, there is a strong need to engage scientists and engineers from fields not traditionally engaged in energy R&D.

It is essential to enhance the research focus on this longer-term need now because of the long time required to discover and bring new concepts to the point where they are ready to be used-up to 30 years or more. Enhancing this area of activity will require building innovative, new, multi-disciplinary research partnerships among a diverse set of scientific disciplines. Building such innovative partnerships will require new approaches to funding and nurturing such activities. That is the goal of this initiative.

The initiative would fund a two-phased enhancement of fundamental science and technology research on novel sequestration systems for integrated approaches involving energy production and conversion with CO_2 capture, reuse and conversion. It is a 10-year program of $150-200M, with the first 5 years of exploratory science and technology funded at $10M per year. The second 5 year phase would fund proof-of-concept testing of those few concepts identified in the first phase as most-promising, Federal funding for the cost-shared 5 year phase would be $20-25M per year.

Key features of this initiative include the following:

- The competitive solicitations of concepts would seek ideas from a broad cross-section of the scientific and technologic communities. Emphasis would be placed on multi-disciplinary team research focusing on revolutionary discoveries.
- The broad academic research community would be encouraged to participate. The initial 5 year phase would not require cost-sharing, although it would be encouraged.
- The solicitations would emphasize truly new pathways as opposed to evolutionary developments based upon traditional concepts.
- Significant emphasis would be given to research to better understand the natural processes (biogeochemical, and microbiological), by which carbon is converted, recycled and reused in natural systems, particularly in deep geologic settings.

VI. TECHNOLOGY TIMELINE AND RESOURCE REQUIREMENTS

Consistent with the guidance for white paper presentation, the technology timeline for Capture and Geologic Storage RD&D activities is presented in Figure 2. It shows the key planned results of both the base program and initiatives from the present to 2030. The federal funding resource requirements, including the current base program and the initiatives are summarized in Figure 3. The funding totals are shown in 5-year increments, starting in 2001.

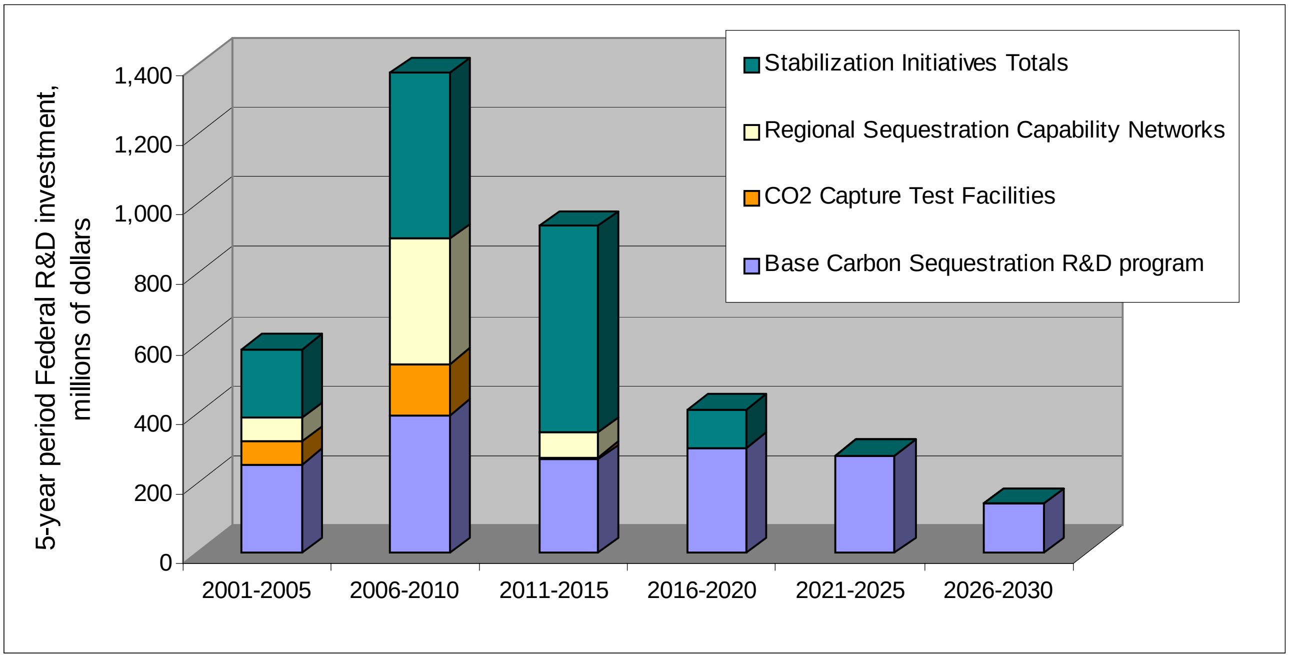


FIGURE 3. PROGRAM FUNDING REQUIREMENTS

The funding profiles reflect a number of assumptions.

- The full set of initiatives is assumed to start in 2003 and proceed as described in Section V.
- Funding requirements of the initiatives in the longer-term era post-2015 are based on an assumption that performance-related, market-based incentives are implemented in the early years, and that they are effective in stimulating the private sector to make both RD&D and deployment investments. Otherwise, higher sustained Federal funding levels would have been assumed.
- The funding estimates are stated in constant, 2001 dollars.

Figure 2. Technology Timeline

Technology Status:

2000*

Performance-related Market-based Incentives
- No incentives

Geologic Storage R&D
- R&D to develop cost-effective technologies, including monitoring & verification for value-added storage is underway.
- Limited exploratory research is underway on other geologic formations.

Capture R&D
- High-cost technologies are available and laboratory scale research is underway with the goal of reducing costs by more than 50%.

Regional Networks
- No regional networks.

Flexible Capture Test Facilities
- Flexible test facilities are lacking in the U.S..

Integrated Pioneer Projects
- No pioneer projects started yet.

Novel Sequestration Systems
- Limited exploratory research is underway.

2005

Performance-related Market-based Incentives
- Are increasing industry investments in cost-shared R&D & Pioneer Projects

Geologic Storage R&D
- Several large-scale field tests & development of monitoring & verification technologies for value-added geologic storage underway.
- Significant scientific & technologic progress being made on other geologic formations.

Capture R&D
- Proof-of-concept tests completed on capture systems which reduce cost by over 50%.

Regional Networks
- Established in several regions to increase the rate of technology diffusion & adaptation to unique regional needs & opportunities.

Flexible Capture Test Facilities
- Operations provide process developers & users critical cost & performance data for scale-up.

Integrated Pioneer Projects
- Initial set of projects in the construction stage.

Novel Sequestration Systems
- Exploratory R&D has identified several Novel Sequestration systems for initial proof-of-concept/field testing.

2010

Performance-related Market-based Incentives
- Private sector R&D cost-sharing & pioneer project investments significantly increased.

Geologic Storage R&D
- Scientific and technologic progress for storage in other geologic formations successful at the proof-of-concept level.

Capture R&D
- Broad set of cost-effective capture technologies suitable for all large point sources developed and tested at a scale sufficient for industry to proceed with commercial scale projects.

Regional Networks
- Significantly advancing regional capabilities and capacities for adapting sequestration techniques to unique regional needs and opportunities.

Flexible Test Facilities
- Testing of several new capture technologies has been completed.

Integrated Pioneer Projects
- A significant number are operational at representative locations along with independent monitoring and verification of the storage.

Novel Sequestration Systems
- Several potentially cost-effective novel sequestration systems are being tested at the proof-of-concept stage.

2020

Performance-related Market-based Incentives
- Are leading to widespread commercial deployment of "first generation" integrated capture & storage projects.

Geologic Storage R&D
- The science & technology base, including large-scale field testing & verification for storage in other geologic formations has been established & selective commercial deployment is starting.

Capture R&D
- Cost-effective technology, for value-added geologic storage widely available and deployed. Technologies for other geologic storage options are beginning to penetrate the market.

Regional Networks
- Are now fully self-sustaining

Flexible Test Facilities
- Are now fully self-sustaining

Integrated Pioneer Projects
- A set of integrated capture & storage representatives of the regional, geologic, and CO2 source diversity across the U.S. have been operational employing "first generation" technologies.

Novel Sequestration Systems
- Several cost-effective novel sequestration systems have been field tested and verified as ready for commercial deployment.

2030, Transition & Beyond

Performance-related Market-based Incentives
- Second generation technologies are being deployed widely.

Geologic Storage R&D
- Cost-effective science & technology for storage in total set geologic formation types fully developed and widely deployed.

Capture R&D
- Second generation of cost-effective capture technologies suitable for all types of energy production and conversion sources are widely deployed.

Regional Networks
- Continue to provide focal points for the adaptation of capture, storage and novel sequestration systems to the unique regional needs and opportunities.

Flexible Test Facilities
- Are fully self-sustaining.

Integrated Pioneer Projects
- A CO2 transport infrastructure is fully operational
- Commercial scale projects are standard industrial practice for all new and retrofit construction of energy production, conversion and use facilities.

Novel Sequestration Systems
- A broad portfolio of novel sequestration systems are fully developed & are being selectively deployed for both large point sources and distributed sources.

GHG Stabilization End-State**

- A large-scale market for sequestration technologies exists and sustains a U.S.-based industry that is the global leader.
- The full portfolio of third generation sequestration technologies are being fully deployed in a cost-effective manner, including novel sequestration systems that incorporate reuse and conversion.
- Continuing public-private R&D is reducing the cost & expanding the range of applicability of sequestration systems.

*** Recent Accomplishments, Demos, Current Research**
**** Net-Zero Emissions of Greenhouse Gases**

VII. Supporting Information: Projects, Participants and Cost-Share

The following table presents projects, performers, and cost-share for the current research portfolio. The portfolio has 60% non-DOE cost sharing from industry and international participants.

Table 2. Carbon Sequestration Research Portfolio

Project: Title, Start Date, Description, Participants	Thousands of $	
	Industry	Federal
CO_2 Capture and Separation		
Integrated Research and Development, 2001. Demonstrate the feasibility of capturing CO_2 from a variety of fuel types and combustion sources and storing it in unmineable coal seams and saline aquifers. Establish guidelines for safe geologic sequestration. [BP Corporation]	8,800	5,000
Advanced Oxy-fuel Boilers and Process Heaters, 2001. Develop a novel "oxy-fuel" boiler – a new boiler design that incorporates a membrane to separate oxygen from the air which is then used for combustion. [Praxair, Tonawanda, NY]	1,800	4,100
Oxygen Firing in Circulating Fluidized Bed Boilers, 2001. Test a way to produce concentrated CO_2 by firing oxygen (rather than air) in an advanced boiler. [Alstrom Power]	350	1,400
Dry Regenerable CO_2 Sorbents, 2000. Develop a CO_2 separation technology that uses a regenerable, sodium-based sorbent to capture CO_2 from flue gas. [Research Triangle Institute, Church and Dwight, Inc.]	240	810
CO_2 Selective Ceramic Membrane for Water-Gas-Shift Reaction, 2000. Develop a high temperature membrane to enhance the water-gas-shift reaction efficiency, while recovering CO_2 for sequestration. Integrates gasification combined-cycle power generation systems. [Media and Process Technology Inc., University of Southern California]	180	720
Computer Model to Enable Evaluation of Power Plant Capture Options, 2000. Develop a computer model that will enable different options for capture of CO_2 from a power plant to be systematically evaluated, including pipeline transport costs. [Carnegie Mellon University]	180	720
Recovery of CO_2 in Advanced Fossil Processes Using a Membrane Reactor, 1999. Construct an inorganic, palladium-based membrane device that reforms hydrocarbon fuels to mixtures of hydrogen and CO_2 and separates hydrogen. [Research Triangle Institute]	--	500
Electricity Generation Using a Metal Oxide Reducing Agent, 1999. Develop an advanced fossil fuel conversion process that uses gasified coal or natural gas to reduce a metal-oxide sorbent, producing steam and high-pressure CO_2, ready for sequestration. This concept, also known as chemical looping, produces heat in the metal oxide regeneration step, which can be used to generate additional electricity. [TDA Research Inc., Wheat Ridge, CO]	--	500
Geologic Storage		
Sequestration of CO2 in Unmineable Coal Seams, 2001. Demonstrate a CO2 injection technology using "slant hole" drilling to drain natural gas from unmineable coal seams. Upon drainage of 50-60% of the CH4, CO2 will be injected into some of the slant-hole wells [Consol, Inc.]	1,900	6,800
Weyburn Sequestration Project: Geologic Reservoir Mapping and Assessment, 2001. Measure and study the movement of injected CO_2 at the Weyburn field with the goal of expanding the knowledge base of the capacity, transport, fate and storage integrity of CO_2 injected into geological formations. [Dakota Gasification Company, Bismarck, North Dakota]	22,500	4,000
Deep Unmineable Coalbeds, an Integrated Approach and Commercial-Scale Field Demonstration, 2000. Use existing ECBM recovery technology to evaluate the viability of storing CO_2 in deep unmineable coal seams in the San Juan Basin in northwest New Mexico and southwestern Colorado. Apply the knowledge gained to verify and validate gas storage mechanisms in coal seams, and to develop a screening model to assess CO_2 sequestration potential. [Advanced Resourced International, BP, Burlington Resources, and Kinder Morgan]	5,700	1,400
Evaluate CO2 Storage Potential in Coal Seams in Alabama, 2000. Develop a broad-based geologic screening model to quantify the CO_2 storage potential of the Black Warrior coalbed methane region in Alabama, and apply the model to identify additional sites with high CO_2 storage potential. [Geologic Survey of Alabama]	610	790

Project: Title, Start Date, Description, Participants	Thousands of $	
	Industry	Federal
Sequestration of CO_2 in a Depleted Oil Reservoir, 2000. Use computer simulations, laboratory experiments and geophysical monitoring to better understand, predict and monitor the migration and ultimate fate of injected CO_2 in an oil reservoir at a field demonstration site in southeastern New Mexico (West Pearl Queen field). [Los Alamos & Sandia National Laboratories, NMT/PRRC, Strata Production Co.]	800	2,400
Natural Analogs for Geologic CO_2 Sequestration (NACS), 2001. Perform a multi-disciplinary geologic and engineering study of U.S. CO_2 deposits to 1) evaluate the safety and security of geologic sequestration, 2) adapt specialized CO_2 operations technology to an emerging sequestration industry, and 3) document analogs for public review. [Advanced Resources International, Inc.]	600	900
Chemical Sequestration of CO_2 in Deep Saline Formations in the Midwest United States, 1999. Examine factors that affect chemical reactions that CO_2 undergoes while it is stored in underground saline formations, specifically reactions that convert CO_2 to a stable solid. [Battelle Laboratories]	--	550
New Techniques for Injecting CO_2 into Saline Formations, 2000. Create a novel well-logging technique using nuclear magnetic resonance to characterize geologic formations. Explore the use of hydraulic fracturing to improve the permeability of saline formations and thus lower the cost of CO_2 injection. [Texas Tech University]	700	3,400
Reactive, Multiphase Behavior of CO_2 in Saline Formations Beneath the Colorado Plateau, 2000. Conduct an in-depth study of deep saline formations in the Colorado Plateau and Rocky Mountain region with the goal of determining how much CO_2 can be stored, what happens to the stored gas, and the long-term environmental risks associated with the storage. [University of Utah]	850	340
Database of Saline Formations in the US Amenable to CO2 Storage, 1999. Develop a database of saline formations in the U.S. that are likely amenable to CO_2 storage. [University of Texas at Austin]	--	290
Digital Spatial Database to Catalogue Geologic Sequestration Sites in the Midwest, 2000. Develop a digital spatial database that catalogues information relating to CO_2 sources and geologic sequestration sites in Illinois, Indiana, Kansas, Kentucky and Ohio. [University of Kansas, Lawrence, KS]	920	2,300
Novel Sequestration Systems		
Enhanced Practical Photosynthesis CO2 Mitigation, 2000. Demonstrate the technical and economic feasibility of an enhanced photosynthetic system that uptakes CO_2 from flue gases at power plants. The systems will separate incident sunlight into spectral regions to maximize cyanobacterial growth. [Ohio University]	240	1,100
Capture and Sequestration of CO2 from Stationary Combustion Systems by Photosynthesis of Microalgae, 2000. Characterize types of flue gas and determine what separation and clean-up technologies are necessary to maximize dissolution of CO_2 to microalgae. Design and industrial-scale sequestration system for combustion units. Model the sequestration process to perform an economic analysis and provide cost-effective solutions. [Physical Sciences, Inc.]	680	170

VIII. REFERENCES

1. The 1999 Gross Domestic Product was $9.25 trillion (U.S. Department of Commerce's Bureau of Economic Analysis). Total energy consumption in 1999 was 96.14 Quad Btus (EIA see below), or 28.176 trillion KWhs. 28.176 trillion kWh / $ 9.25 trillion is 3.04 KWh per dollar spent.
   Coal, oil and natural gas consumption data is from AEO 2001 p. 127 Table A1, which shows an estimated increase from 81 quads in 1999 to 112.4 quads in 2020, or 38%. ((112.4-81)/81 = .383).
   CO_2 emissions data is from AEO p. 97, Fig. 125. In 1999 CO_2 emissions were 1,511 MMTCE and in 2020 are expected to be 2,041 MMTCE, an increase of 35% ((2041-1511)/1511 = .35).

Total	1999	2020	Change
Fossil Quad	81	112.4	38 %
Total Quad	96.14	127	32 %
CO_2 MMTCE	1,511	2,041	35 %

2. Ice core data is obtained from Siple Station, West Antarctica. Pre-1745 samples show a relatively stable concentration of CO_2 at 279 ppm. Current levels, obtained from the Observatory Station at Mauna Loa, show a concentration of 368 ppm, an increase of 32% ((368-279)/279 = .318).

Year	1745	1804	1838	1894	1949	(1999)
CO_2 ppm	279	280	286	297	311	(368)

3. Atmospheric data is obtained from Mauna Loa Observatory Station, in Hawaii, NOAA.

Year	1996	1997	1998	1999
CO_2 ppm	362.7	363.8	366.7	368.4

4. Global warming potential data is obtained from the Energy Information Administration *Emissions of Greenhouse Gases in the United States 1999.* P. viii, Table ES2 "US Emissions of Greenhouse Gases, Based on Global Warming Potential."

Gas MMTCE	1999	Percent
CO_2	1,527	83%
Other	306	17%

5. Herzog, Howard, E. Drake and Eric Adams. "CO_2 Capture, Reuse and Storage Technologies for Mitigating Global Climate Change," *MIT 1997 White Paper*.

6. *Carbon Sequestration: State of the Science,* U.S. DOE Office of Science and Office of Fossil Energy, April 1999.

7. *Capture and Geologic Sequestration: Progress Through Partnership,* workshop report, U.S. DOE, BP AMOCO, and IEA/GHG, September 1999

8. Economics Benefits of a National Strategy and R&D Program in Carbon Sequestration, D. Beecy, V. Kuuskra, P. DiPietro; *presented at the First National Conference on Carbon Sequestration,* May 14-17, 2001.

9. Large point CO_2 emitters, electric generators (including co-generators) and large industry (cement manufacture), account for 1/3 of all US CO_2 emissions. According to the *EIA Emissions of Greenhouse Gases in the United States in 1999,* pp 28 and 29, tables 11 and 12, this adds to 625 MMTCE, or 2,291 MMTCDE. This is about 34% of total U.S. 1999 anthropogenic GHG emissions, which were 6,719.4 MMTCDE (p vii).

10. Office of Energy Research, *Carbon Management, Assessment of Fundamental Research Needs*. US Department of Energy, Washington D.C., 1997

APPENDIX: TECHNOLOGY PROFILES

CO_2 CAPTURE AND SEPARATION

Technology Description

Fossil and biomass based energy conversion processes convert hydrocarbon materials (i.e., substances consisting mostly of carbon and hydrogen) into carbon dioxide and water. The goal of CO_2 capture and separation is to produce relatively pure CO_2 as a by-product, preferably at pressures suitable for storage or reuse.

System Concepts

- Post-combustion capture. A chemical or physical separation process extracts CO_2 from the flue gas of a conventional air-fired combustion process (CO_2 is present in concentrations ranging from 3% to 12%).
- Oxy-fuel combustion. Pure oxygen or oxygen-enriched air is charged to the combustion chamber, producing concentrated CO_2 in the boiler effluent. A portion of the CO_2 is recycled to control the boiler operating temperature.
- Pre-combustion de-carbonization. Hydrocarbons are gasified to produce a synthesis gas made up primarily of hydrogen and CO_2, which can be separated before the hydrogen is utilized.
- Other advanced system concepts in which fuel processing and CO_2 capture are integrated into a single stage.

Representative Technologies

- Liquid amine chemical absorbents are the conventional technology for capturing CO_2 from flue gas process streams. The stream containing CO_2 is contacted with a solution of amine and water. The amine and the CO_2 undergo a chemical reaction forming a water-soluble rich amine. The rich amine solution is pumped to a desorber where it is heated, reversing the reaction and releasing pure CO_2 gas. The recovered amine is recycled.
- Other technologies include: cryogenic distillation, polymer membranes, ceramic membranes, carbon absorbents, sodium absorbents, hydrides, and lithium silicate.

Technology Status/Applications

- Amine systems are used in numerous industrial applications to capture CO_2 from fossil fuel conversion systems for use as a commodity chemical. Cryogenic and carbon absorbent systems have been built commercially.
- Oxygen-enriched combustion, chemical looping, advanced membranes, and sorbents are being developed.

Current Research, Development and Demonstration

RD&D Goals

- By 2008 demonstrate 90% reduction in the cost of CO_2 capture for new builds (The overall cost reduction goals include both equipment cost and parasitic load.)
- By 2010 demonstrate 75% reduction on the cost of CO_2 capture for retrofit applications.
- In the long term reduce the cost of capture so that it increases the cost of energy services by 5% or less.

RD&D Challenges

- Existing stock of air combustion fossil fuel conversion systems produce dilute CO_2, 3-12 volume percent.
- Solid fuel gasification has shown reliability problems
- Transport and/or storage systems may require highly pure CO_2 product
- Loss of CO_2 temperature and pressure across capture system

RD&D Activities

- Laboratory-scale experiments with advanced amines, ceramic membranes, high-temperature polymer membranes, vortex gas/liquid separator, ammonium bicarbonate, carbon absorbents, and electrochemical pumps.
- Pilot-scale tests; novel oxy-fuel boiler, CO_2/water hydrate process, sodium-based CO_2 sorbent, metal redox power generation process.

Past Successes and Benefits

- Over a short three-year period of time, a strong portfolio of research projects has been developed with over 50% private-sector cost-share.
- Successfully engaged the international community through participation in the IEA GHG Programme, the CO_2 Capture Project with the European Commission and other international participants, and other collaborations with Canada, Australia, and Japan.

Commercialization and Deployment
• CO_2 is currently captured from both combustion and gasification systems for use as a commodity chemical.

Potential Benefits and Costs
Carbon Reductions • Approximately 1/3 of the U.S. CO_2 emissions, or about 2.3 billion tons of CO_2 per year, come from large point sources that are amenable to capture. With possible upstream de-carbonization of transportation and space heating fuels the potential for CO_2 capture and storage is even higher. • If in the future deep reductions in carbon emissions are deemed necessary as a part of a global strategy to reduce the concentration of GHGs in the atmosphere, a successful carbon sequestration technology development effort could produce billions of dollars of benefits in the form of a lower cost of emissions reductions compared to alternatives. **RD&D Expenditures** **Carbon Sequestration Program Overall** • FY 2000 6 MM$ • FY 2001 19 MM$ • FY 2002 31 MM$ **Nonenergy Benefits and Costs** • CO_2 capture systems could be integrated with NO_x, SO_x, HG, and particulate matter emissions reduction. • Retrofit capture could be instrumental in improving the markets for U.S. technology and services in developing countries with significant coal resources. **Expected Cost Per Ton of Carbon Emissions Avoided** • Long-term goal 10 $/ton carbon emissions avoided.

Key Federal Actions
• Fund cost-shared R&D at the laboratory scale to produce new and innovative approaches to post-combustion capture • Working with industry, conduct pilot-scale experiments to verify the performance of promising technologies. • Integrate technology development effort with the development of control systems for criteria pollutants • Option for New Initiative: Regional Sequestration Capability Network Regional challenges with regional solutions are the rationale for establishing a multi-site *regional carbon sequestration (RCS) network.* The purpose of the RCS network is to establish regional public-private partnerships to facilitate science and technology development and public outreach appropriate to each major sequestration region. This would include a focus on providing information to the public. The RCS network will involve academia, national laboratories, energy producers and users, and state and local agencies. The network would help provide region-specific scientific data and options to ensure the use of environmentally sound practices and the long-term safety of the sequestration alternatives being considered. • Option for New Initiative: Assuring the Viability of Carbon Capture and Sequestration Phase I: Flexible Test Facilities for CO_2 Capture. Several CO_2 Capture and Separation Test Facilities are necessary to facilitate and accelerate development of technologies to reduce CO_2 emissions, especially those produced by the energy sector, to the point of commercial. Currently, there is a lack of adequate such test capabilities in the U.S. Facilitation and implementation of these test facilities would be through cost-shared, public-private partnerships including consortia of universities, industry (including technology developers and users), and governments dedicated to surmounting technical and economic barriers. • Option for New Initiative: Assuring the Viability of Carbon Capture and Sequestration Phase II: Integrated Capture and Storage Pioneer Plants. This initiative would fund a series of "first-of-a-kind " integrated projects consisting of CO_2 capture, transport (as needed), storage, and independent monitoring and verification of the amounts stored. It would provide the nation with key benefits: demonstrate the environmental acceptability and public acceptance of these approaches; provide monitoring and verification of the amount of CO_2 sequestered; and provide assurance of cost-effectiveness and best use of national resources in mitigating global climate change.

CO_2 STORAGE IN GEOLOGIC FORMATIONS

Technology Description

Large amounts of CO_2 (a billion tons per year) may need to be stored as a part of a future global atmospheric stabilization strategy. Depleting oil wells and unmineable coal-bearing formations provide two potential types of storage reservoirs for CO_2. R&D is focused on adapting these geological formations for safe, maximum storage. Saline formations, organic-rich shales and other non-conventional geologic structures also have potentially enormous CO_2 storage capacities. Research is focused on learning more about these formations to utilize them for CO_2 storage.

System Concepts

- CO_2 is captured from large point sources of anthropogenic emissions, transported, and injected into a depleting oil well or an unmineable coal seam, saline formation, depleting gas well, shale formation or other geologic structure.
- Storage may entail geochemical reactions that tend to form carbonates in silicic host rock, enhancing containment.
- Maintaining the oil formation's or coal seam's pressure contains the CO_2 in the geologic formation.
- Impurities in the CO_2 stream (e.g., sulfur, nitrous oxides, nitrogen) may be acceptable in certain geologic formations.

Representative Technologies

- Natural gas storage in aquifer formations provides relevant capability and experience.
- Technologies will borrow extensively from the petroleum industry in drilling, stimulation, and completion of injection wells; processing, compression, and pipeline transport of gases; operational experience of CO_2 injection; and subsurface reservoir engineering and characterization.

Technology Status/Applications

- The Mt. Simon reservoir underlying Illinois, Indiana, Michigan, Kentucky, and Pennsylvania has been approved for industrial waste disposal and underlies a region with numerous fossil energy power plants.
- There is industrial experience with over 400 wells for injecting industrial wastes into saline formations.
- The petroleum technology is currently injecting 30 million tons per year of CO_2 into geologic formations for improving oil recovery.

Current Research, Development and Demonstration

RD&D Goals

- Develop underground CO_2 storage repositories capable of accepting a billion tons of CO_2 per year.
- Develop publicly-accepted monitoring and verification protocols and risk assessment technology.
- Demonstrate that CO_2 storage underground is safe and environmentally acceptable.
- Demonstrate an effective business model for CO_2 storage in depleting oil and gas reservoirs and deep unmineable coal seams.

RD&D Challenges

- Develop the capability to inject CO_2 into saline formations with low permeability.
- Harness geochemical reactions to enhance containment.
- Develop injection practices that preserve cap integrity.
- Develop an understanding of the CO_2 properties of shales and other hydrocarbon bearing formations.
- Develop ability to track the flow transport and fate of CO_2.
- Develop the ability to predict CO_2 storage capacity in a variety of formations.
- Develop field practices that optimize CO_2 storage and resource recovery.
- Develop a better understanding of the chemistry of coal and CO_2 .

RD&D Activities

- Laboratory study of geochemical reactions involving CO_2 .
- Study of natural analogs of geochemical CO_2 conversion. Study of rock samples from CO_2 bearing geologic. formations to better understand in situ geochemical/geobiological reactions.
- Development of CO_2 tracking technology, e.g., sonic, chemical tracers.
- Study of CO_2 transport in the Sleipner Vest gas field, via IEA GHG Programme.
- Novel injection techniques to increase CO_2 storage in saline formations.
- CO_2 storage in coal beds. ARI and industry consortium, geologic data and reservoir model in the San Juan Basin; Consol, horizontal drilling and screening model for Black Warrior.
- CO_2 storage in oil reservoirs. Weyburn, reservoir mapping; West Pearl Queen, CO_2 monitoring and simulation.

Past Successes and Benefits
• Surveyed and cataloged the saline formations underlying the United States. • Initiated a pilot-scale test of CO_2 storage in a depleted gas reservoir. • Initiated several field tests with key industrial companies participating and providing cost-share: Consol Inc. – Appalachia Basin; ARI - San Juan Basin; Strata Production – Permian Basin; PanCanadian Resources – Weyburn, Canada.
Commercialization and Deployment
• Since 1999 Statoil has been injecting CO_2 at a rate of 1 million tons per year into the Sleipner Vest gas field in a sandstone aquifer 1000m beneath the North Sea. • About 70 oil fields worldwide inject CO_2 for enhanced oil recovery. • CO_2 from the Dakota gasification plant is transported to the Weyburn field in Canada for enhanced oil recovery.
Potential Benefits and Costs
Carbon Reductions • The CO_2 storage capacity of depleted oil and gas reservoirs in the United States is 120 to 150 billion tons of CO_2 . • Saline formations alone have the potential to store several hundred years worth of CO_2 emissions. • The storage capacity of shale formations with high organic content has not been estimated, but the shale resources are plentiful, comparable to coal. • With a fully-funded R&D effort and a CO_2 emissions reduction credit of $10 to $15 per ton CO_2, depleted oil fields and unmineable coal seams could store 400 million tons per year of CO_2 by 2020. **RD&D Expenditures** **Carbon Sequestration program Overall** • FY 2000 6 MM$ • FY 2001 19 MM$ • FY 2002 31 MM$ **Nonenergy Benefits and Costs** • CO2 storage depleted oil and gas reservoirs could provide significant incremental production of domestic energy: – 1 million barrels per day crude oil production (in 2020), – 2 Bcf per day natural gas production (in 2020), and – $12 billion per year improvement in the U.S. trade balance through displacement of imports. **Expected Cost Per Ton of Carbon Sequestered** • The cost of CO_2 capture and storage is on the order of $50 per ton, with 75% of the total cost in capturing CO_2 from anthropogenic sources and delivering it to the injection site. Early CO_2 storage applications will utilize opportunity sources of CO_2 (e.g., natural gas processing, steam reforming, ethanol manufacture). Value added production of oil and gas can help offset the cost of CO_2 capture, delivery and storage.
Key Federal Actions
• Develops reliable CO_2 monitoring, verification and mitigation technology. • Sponsor data collection and publicly acceptable methodology for risk assessments. • Fund field test of CO_2 injection and long-term storage techniques for saline formations, depleted oil and gas fields and unmineable coal seams. • Co-fund field test of advanced CO_2 injection techniques into underground formations. • Understand effects of CO_2 injection on cap rock integrity and reservoir properties. • Develop CO_2 technology for verifying CO_2 storage permanence. • Option for New Initiative: Enhanced Science and Technology for Geologic Storage. The scientific knowledgebase and technologies for the less well-researched types of geologic storage need to be better defined. While some of the topics are currently being addressed in the Sequestration R&D Program, the depth and pace of the research is not consistent with the goals of achieving a robust science and technology pathway to stabilization. This initiative would increase both the scope and pace of research in these areas.

NOVEL SEQUESTRATION SYSTEMS

Technology Description

In the long-term, CO_2 capture can be integrated with geologic storage and/or conversion. Many naturally occurring CO_2 conversion reactions are attractive but too slow for economic chemical processes.

System Concepts

- Using impurities in captured CO_2 (e.g., SO_x, NO_x) or additives to enhance geologic storage. Possible opportunity to combine CO_2 emissions reduction and criteria pollutant emissions reduction.
- Conducting reactions on CO_2 while it is being stored underground can alleviate the problem with slow kinetics.
- Rejected heat from electricity generation and CO_2 compression can help drive CO_2 conversion process.

Representative Technologies

- Capture of CO_2 from flue gas and algal conversion to biomass
- Capture of CO_2, storage in a geologic formation, and in-situ biological conversion to methane

Technology Status/Applications

- Conceptual.

Current Research, Development and Demonstration

RD&D Goals

- Demonstrate viable chemical or biological conversion approaches at the laboratory scale
- Develop robust conceptual designs for integrated capture, storage, and conversion systems

RD&D Challenges

- CO_2 conversion reaction kinetics are slow, energy requirements high
- For biological in-situ CO_2 conversion, must provide food and remove waste

RD&D Activities

- Laboratory and pilot-scale experiments with biological and chemical conversion
- Conceptual studies of integrated systems and in-situ CO_2 conversion

Past Successes and Benefits

- Several cost-shared research projects have been initiated.

Commercialization and Deployment

- None

Potential Benefits and Costs

Carbon Reductions

- In the long-term regenerable carbon-based energy systems could provide all of the United States' energy needs.

RD&D Expenditures
Carbon Sequestration Program Overall

- FY 2000 6 MM$
- FY 2001 19 MM$
- FY 2002 31 MM$

Nonenergy Benefits and Costs

- Sequestered carbon is converted to fuels or useful products

Expected Cost Per Ton of Carbon Sequestered

- 10 $/ton

Key Federal Actions

- Provide funding for early stage R&D, and pilot scale testing of promising technologies
- Option for New Initiative: Science and Technology for Novel Sequestration Systems
  This initiative addresses the longer-term needs for revolutionary new technologies which can combine energy production and conversion with the reuse and conversion of CO_2 as an alternative to emitting CO_2 to the atmosphere. It encompasses science and technologies to address small-scale sources, such as distributed energy systems as well as larger-scale. This is the longest-term, highest-risk portion of the Carbon Sequestration Program portfolio. It has a time horizon of up-to-30 years. Hence, it is reasonable to assume that there is little incentive for private sector investments in this area in the near-term.
  Moreover, since it will require significant advances and discoveries in science, before technology can be developed, there is a strong need to engage scientists and engineers from fields not traditionally engaged in energy R&D.
  It is essential to enhance the research focus on this longer-term need now, because of the long time required to discover and bring new concepts to the point where they are ready to be used--up to 30 years or more. Enhancing

this area of activity will require building innovative, new, multi-disciplinary research partnerships among a diverse set of scientific disciplines. Building such innovative partnerships will require new approaches to funding and nurturing such activities. That is the goal of this initiative.