CARBON SEQUESTRATION

Overview and Summary of Program Plans

DRAFT

April 2000

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Overview and Summary of Program Plans

I. National Needs

The availability of clean, affordable energy is essential for the prosperity and security of the United States and the world in the 21st century. About 85% of U.S. energy is derived from fossil fuels, and continued reliance by the U.S. — and the world — is forecast well into the 21st century. At the same time, the Intergovernmental Panel on Climate Change has stated that ". . . the balance of evidence suggests that there is a discernable human influence on global climate."

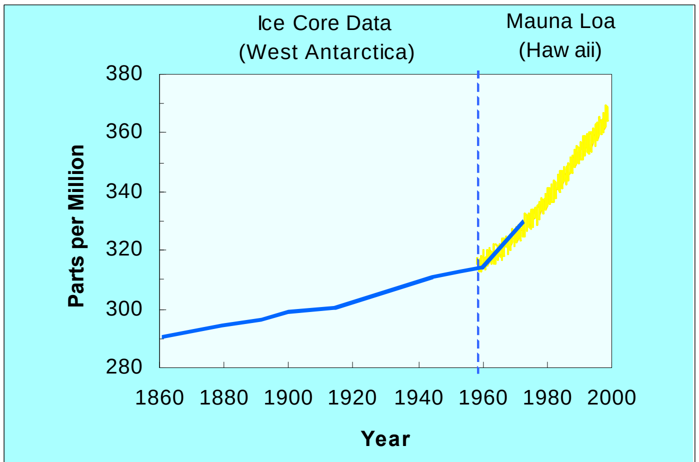
A. The Greenhouse Gas Stabilization Issue

The concentration of carbon dioxide (CO_2) in the atmosphere is rising and the increase correlates to the industrialization of the world. The use of fossil fuels is one of the major contributing factors (see Figure 1). CO_2 is a common substance that is part of our everyday lives; it is the "dry ice" used for cooling and movie special effects, and it provides the carbonation in our sodas. As part of the world's fauna, we breathe in O_2 from the atmosphere and exhale CO_2. Plants essentially do the reverse, taking up CO_2 and releasing O_2. The carbon from the CO_2 is incorporated (or sequestered) into plant tissue. Over the long term, most of the CO_2 in the atmosphere is absorbed by the ocean.

There is a wide range of natural CO_2 sources and sinks (storage). Sources, for example, include volcanic activity and decomposition of plant material, and sinks include oceans, soils, and plant life. Emissions of CO_2 caused by human activity are relatively small in scale compared to natural global CO_2 respiration (currently about 3%). Nonetheless, it is a fact that, as shown in Figure 1, the concentration of CO_2 in the atmosphere has been rising.

Due to growing concern about the increased concentration of greenhouse gases in the atmosphere and possible adverse impacts, in 1992 the United States and 160 other countries established the Framework Convention on Climate Change (FCCC), including the treaty commonly referred to as the Rio Treaty. The treaty calls for,

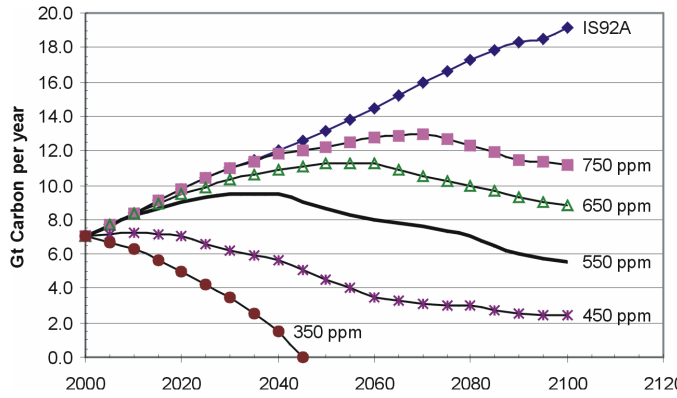
> " . . . stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."



Data sources: Ice core data obtained at the Siple Station, published by Neftel, et al., 1985; Data from the Mauna Loa Observatory obtained from the NOAA w eb page.

Figure 1. Atmospheric CO_2 Concentration

While the appropriate level of greenhouse gases that represents "stabilization" is open to debate, a range of 350-750 parts per million (ppm) has been widely discussed. Figure 2 displays annual global rates of emission of carbon which would result in such a range of atmospheric concentrations over the next 100 years. The midpoint of this range, 550 ppm, is used as a reference scenario for program planning.



Source: Wigley, Richels, and Edmunds, *Nature,* Volume 379, January 18, 1996.

Figure 2. Annual Emission Levels to Achieve CO_2 Stabilization

It is well accepted that even modest atmospheric stabilization scenarios will require significant reduction in greenhouse gas emissions over the next 50-100 years - on the order of 50 to 90% below business-as-usual.

The challenge is to enable continued economic growth through affordable energy while also meeting environmental goals. Importantly, as Figure 2 demonstrates, atmospheric stabilization does not require wholesale introduction of zero-emission systems in the near-term. There is time for R&D to work—time to develop *cost-effective* technology over the next 10-15 years that could be deployed when and if deep reductions in carbon emissions are deemed necessary. The carbon sequestration option could save the United States economy trillions of dollars.

B. Carbon Sequestration - the Third Option

To achieve whatever level of atmospheric concentration is ultimately deemed acceptable, there are three basic options: (1) improve the efficiency of energy production and end use (2) reduce the carbon content of fuels through a combination of decarbonization, fuel switching, and increased use of noncarbon energy systems (e.g., renewables and nuclear), and (3) reduce net emissions by sequestering carbon, either through enhancing natural sinks (e.g., forestation) or by capturing the CO_2 emitted from fossil-based energy systems and storing it in geologic formations or the deep ocean or converting it to benign solid materials through biological or chemical processes.

To date, the United States energy R&D portfolio has emphasized increased efficiency in energy production and end use, and greater use of lower carbon fuels plus noncarbon energy systems, all of which are promising options. It appears unlikely that improved energy use efficiency and reduced-carbon energy production (nuclear, renewable, natural gas) will be sufficient to meet the goal of the Framework Convention on Climate Change. However, if large-scale sequestration which is inexpensive and environmentally benign can be developed, such an aggressive goal may be practicable.

> **U.S. Secretary of Energy**
> **Bill Richardson**
>
> *"I believe we can and should look to...new ways to capture and control the release of carbon. This should become the third option in our 'menu' for future greenhouse gas controls."*
>
> June 23, 1999

Carbon sequestration is a relatively new idea, and many U.S. and international energy producers and users are now recognizing the major role it may play in assuring affordable energy for our nation's and the global economy. If sequestration is to play such a role, a broad spectrum of large-scale, low-cost capture and sequestration systems will be required—not just for new energy capacity for economic growth, but to replace existing capacity in capital-stock turnover.

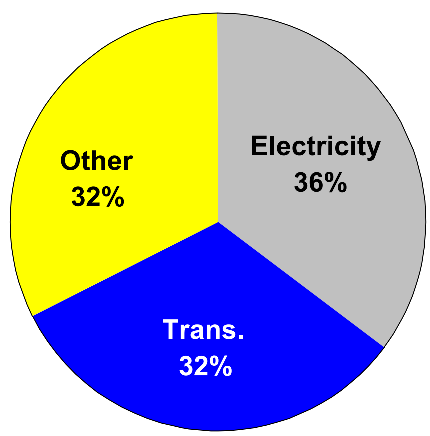
New technologies and approaches are needed to solve the greenhouse gas emissions problem in a cost-effective, safe, and environmentally sound manner. Working closely with U.S. industry, academia, and a worldwide network of energy professionals from other countries, the Carbon Sequestration Program is seeking to create a new policy option - one that will enable us to continue to enjoy the economic and energy security benefits which affordable fossil fuels bring to our Nation's energy mix.

C. Program Drivers

The Rio Treaty, which has been ratified by 160 countries including the United States, provides an international framework for cooperation in stabilizing CO_2 concentrations. In the U.S., the importance of carbon sequestration research has been underscored by the President's Committee of Advisors on Science and Technology (PCAST). The committee's report, *Federal Energy Research and Development for the Challenges of the Twenty-First Century,* recommends increasing yearly budgets for the Sequestration Program " . . . to the vicinity of tens of million."

In March 2000, the U.S. Department of Energy (DOE) published a final comprehensive *Carbon Sequestration Research and Development Report.* The report identifies ". . . key areas for research and development (R&D) that could lead to an understanding of the potential for future use of carbon sequestration as a major tool for managing carbon emissions." This report is the cumulation of a joint effort by the Office of Fossil Energy (FE) and the Office of Science involving the publication of the draft report, "Carbon Sequestration: State of the Science" in April 1999 and a subsequent public/industry workshop.

As shown in Figure 3, the source of CO_2 is roughly 1/3 from electric power generation, 1/3 from transportation, and 1/3 from other sources (industry, commercial, and residential). Carbon sequestration technologies are applicable to the reduction of emissions from electric generation point sources and to the decarbonization of fuels for use in other applications. This includes low-carbon and hydrogen fuels from fossil fuels, for both stationary and transportation uses. In addition, it may be possible to sequester CO_2 directly from the atmosphere by enhancing natural terrestrial and ocean carbon sinks. Hence carbon sequestration addresses all three areas shown in Figure 3.



Data Source: EIA Annual Energy Outlook 2000.

Figure 3. CO_2 Sources in the U.S. Economy, 1998

The main challenges for the Carbon Sequestration Program are to reduce the cost of sequestration, develop a broad suite of sequestration options, and ensure that long-term sequestration practices are effective and environmentally acceptable.

D. The Federal Role

While industry interest in carbon sequestration is strong and growing, the Federal role is critical. The public benefits of maintaining economic growth through affordable energy, while meeting environmental goals, are huge. No company or group of companies could possibly tackle the climate change issue alone. Moreover, the technical risk of carbon sequestration—capture, separation, storage, or reuse—is currently too high. Accordingly, the Federal role in carbon sequestration, through partnering with industry, academia, other countries, and international organizations, will reduce the costs and risks associated with carbon sequestration and provide a significant public benefit.

II. Program Goals

The program goals described below are considered in the context of a future scenario where U.S. and global carbon emissions are reduced to stabilize the concentration of CO_2 in the atmosphere. Using current technology for capture and storage of CO_2 from large point sources, estimates of sequestration costs are in the \$100-300/ton range, and the environmental acceptability is as yet unproven. Reforestation is generally available at significantly less cost, but may be limited.

Given the issues and drivers described above, and assuming a mid-point stabilization of 550 ppm, the following program goals have been established:

- Provide economically competitive and environmentally safe options to offset all projected growth in baseline emissions of greenhouse gases by the U.S. after 2010, with offsets starting in 2015.

- The long-term cost goal is in the range of \$10/ton of avoided net costs for carbon sequestration.

- Provide technology to offset at least one-half the required reductions in global greenhouse gases, measured as the difference in a business-as-usual baseline and a strategy to stabilize concentrations at 550 ppm CO_2, beginning in the year 2025.

The third goal represents the global potential for these technology options if broadly applied by the U.S. and other countries for carbon sequestration.

Figure 4 demonstrates how the goals of this program can relate to potential future policies for achieving emissions reductions. The availability of carbon sequestration can shift the marginal cost (MC) curve for emissions reduction. Also, R&D will produce new information upon which market-based incentives could be employed.

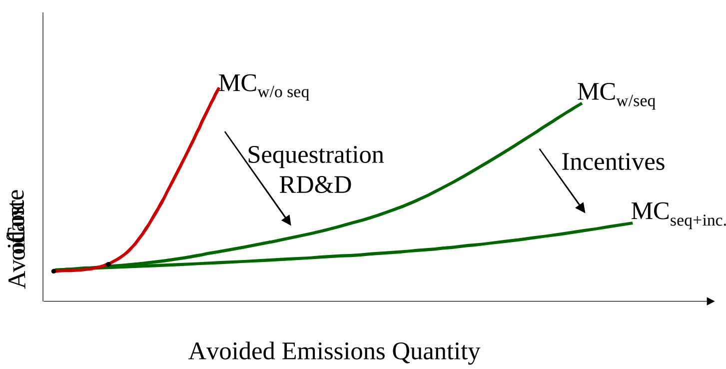


Figure 4. Decreasing the Marginal Cost of Reducing Greenhouse Gas Emissions

III. Program Benefits

The program benefits are based on lowering the cost of a deep reduction in carbon emissions. *If such a reduction is required, the benefits of carbon sequestration are enormous*[1,2]. Without sequestration, deep reductions in emissions are expected to be expensive, and estimates range from $200 to $700 per ton. Moreover, because carbon emissions are constantly growing, even a modest stabilization scenario ultimately becomes significant. Consider a 550 ppm scenario where U.S. carbon emissions above the 2010 level are offset.[3] By 2050 carbon emissions are 34% less than what they would have been without constraint, and the cumulative reduction equals 9.1 billion tons of carbon – that is in addition to an estimated 7 billion tons of emissions reduction achieved through improvements in energy supply and end-use efficiency. If sequestration is used to achieve these reductions at a cost of 10 $/ton instead of other more costly options at an average cost of 300 $/ton, the program benefit through 2050 equals $2.7 trillion.

Time is of the essence. Experience has shown that it takes from 10-30 years to move energy technologies from exploratory research to commercial deployment. At present the evidence of adverse climate impacts is such that immediate and drastic emissions reductions are not perceived to be required. That could change in the future. If pressure to reduce carbon emissions arises before sequestration technology is ready, investments would have to be made in other costly and capital-intensive energy systems, and the opportunity to achieve results with a lower negative impact on the economy will be diminished. Figure 5 shows that the program benefits are reduced significantly under the 550 ppm scenario if the R&D schedule slips from the milestones and goals of the Sequestration Program. However, the program benefit is still high even if sequestration systems fall somewhat short of the 10 $/ton cost goal.

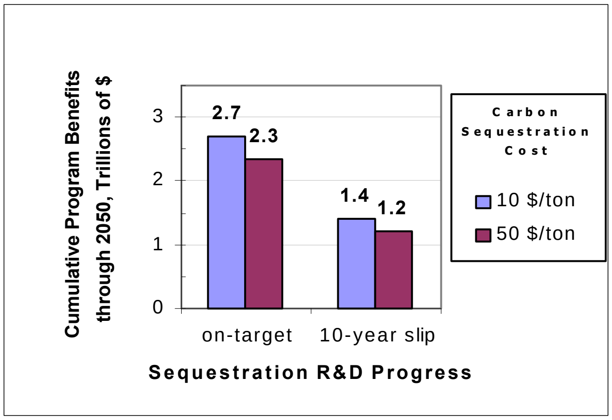


Figure 5. Sensitivity of Benefits to R&D Schedule

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[1]The program benefits analysis, briefly summarized here, is based on U.S. and global carbon emissions projections from EIA and the Intergovernmental Panel on Climate Change (IPCC) and atmospheric stabilization scenarios developed by Wigley, Richels and Edmunds. A full report on the analysis can be found in the proceedings of the Second Annual Dixie Lee Ray Symposium, September 1999 (forthcoming).

[2]Other studies, with slightly different assumptions and methodologies, have also concluded that very large economic benefits would result from low-cost sequestration technologies. For example, *Potential for Advanced Carbon Capture and Sequestration Technologies in a Climate Constrained World*, PNNL, February 2000, projected savings of $1.7 trillion, in 1996 dollars, by the end of this century.

[3]This is a conservatively low basis for a 550 ppm scenario and the program benefits for three reasons. First, the participation of individual countries in a future global stabilization effort is as yet unknown. Second, developing nations would contend that the United States should reduce its emissions much more than 34% by 2050 under a 550 ppm scenario. Third, as Figure 2 shows, the emissions reduction called for in the 550 ppm scenario increases sharply after 2050, which is beyond the analysis time frame used here.

IV. Program Relationships

> **Interest in Carbon Sequestration is Very Strong**
>
> The industry and academic research communities have expressed their interest and willingness to join in partnerships through its response to the first of two submission dates to a Program Solicitation. Over 60 proposals for cost-shared cooperative agreements were received on January 18. The total proposed research amounts to $125 million. Importantly, $50 million of cost-sharing has been proffered by proposers, even though R&D in this area is still in its early stages. This represents a very strong cost-share ratio of 40% in this voluntary program.

The program has built an extensive collaborative network of relationships with private and public sector stakeholders. Within DOE, the program builds on a cooperative effort between FE and the Office of Science which has already resulted in the previously mentioned reports on carbon sequestration. The research pathways defined in these efforts form the structure of the program.

Within FE, the program will combine synergistically with Vision 21 to jointly address the three basic options to reduce CO_2 concentrations. For the critical area of CO_2 capture and separation, the program has important linkages with the Advanced Research & Environmental Technologies Program (renamed the Innovations for Existing Plants Program in the FY 2001 budget). In particular, the potential of integrating CO_2 control with other emissions control systems would provide the option of integrated control at lower cost.

In the area of terrestrial sequestration, which encompasses forestry and enhanced storage in soils and vegetation, FE is working closely with the U.S. Forest Service and the Office of Surface Mining and has established Interagency Agreements with them to cooperate and partner in areas of mutual interest. In the area of geologic sequestration, FE and the U.S. Geologic Survey have a long-standing history of cooperation and collaboration under another Interagency Agreement. As the program proceeds, similar collaborative agreements will be sought with other federal agencies, as well as with state agencies and their representative organizations.

The program has established highly interactive relationships with industry and academic stakeholders. These relationships started with a government/industry/academia workshop hosted by the Massachusetts Institute of Technology in 1998, and include recent activities such as a joint FE/industry/international workshop in geologic sequestration and the selection of cost-shared industry/academic/national lab R&D projects through competitive solicitations. The program combines these activities with international collaboration, including joint work with the International Energy Agency's Greenhouse Gas R&D Programme (IEA/GHG) and its member countries, including our North American neighbor, Canada.

Together, these collaborations provide critical links between the program, industry, end-users, R&D performers, and other Federal and international programs. This provides the necessary foundation for cost-effective partnerships in science and technology planning, development, testing, and verification.

V. Program Strategy

A program that encompasses R&D on a diverse portfolio of sequestration technologies offers the best chance of success, both reducing risks and ultimate costs to the U.S. under a potentially carbon-constrained future.

In the near- and mid-term, the program will develop options for "value-added" sequestration with multiple benefits, such as using CO_2 in enhanced oil recovery operations and in methane production from deep, unmineable coal seams. Over the long-term, the technology products will be revolutionary and require less reliance on site-specific or application-specific factors to ensure their economic viability.

Carbon Sequestration Research at the NETL

The NETL has designated a research focus area on carbon sequestration which will play a key role in the DOE program by providing (1) scientific insights leading to technological options for stabilizing the concentrations of CO_2 and other greenhouses gases, (2) ensuring full attention to the environmental aspects of sequestration options, and (3) providing scientific information for objective system and policy analysis. The focus of R&D activities include:

- Separation and capture of CO_2 from point sources such as fossil power plants
- Sequestration of CO_2 in geologic formations

A carbon sequestration research focus area will be established at the NETL in FY 2001 to serve as a center of competence and related knowledge and analysis for sequestration science and technology options. The research focus area will also perform exploratory studies on advanced chemical and biological concepts, and develop computer-based systems models to assess sequestration approaches developed by the program.

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

The Carbon Sequestration Program focuses on building partnerships. In planning, the program has established a broad spectrum of stakeholder relationships. In implementation, cost-shared partnership agreements with industry, academia, national labs, and other Federal agencies are the primary mechanisms for pursuing the highest-value opportunities in the program portfolio. The primary mechanism for partnering with industry is cost-shared cooperative agreements.

VI. Program Pathways

There are five basic routes to achieve long-term sequestration, as shown in Figure 6. Each of these pathways integrates with the flexible-product, high-efficiency systems being developed in the Vision 21 program. The definition of these pathways as primary opportunities for R&D stems from the collaborative effort with DOE's Office of Science as previously discussed. Together, they cover the entire carbon sequestration spectrum of capture, separation, transportation, and storage or reuse.

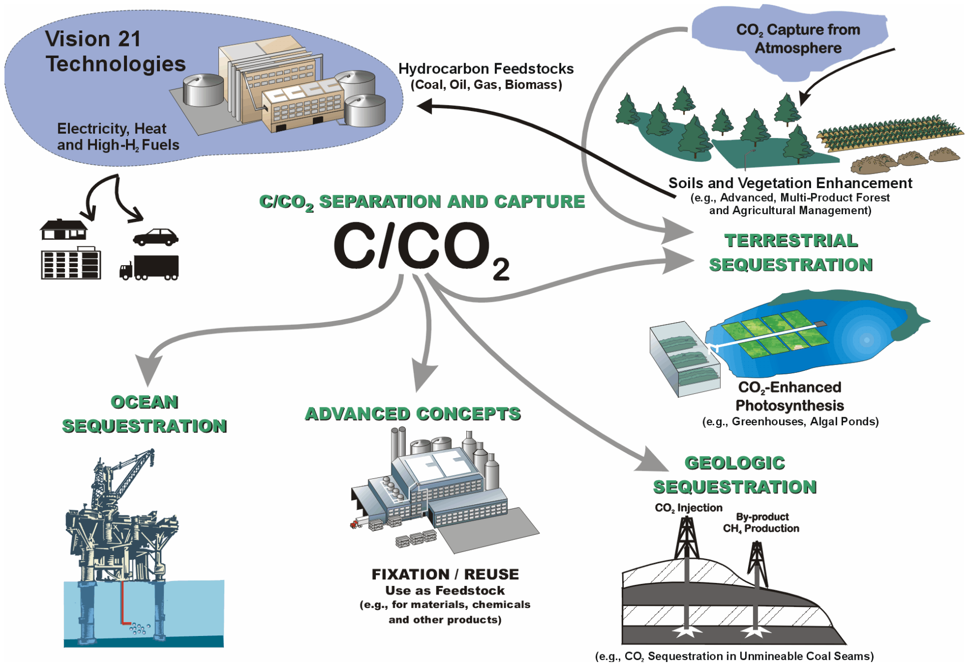

Figure 6. Carbon Sequestration Pathways

These five carbon sequestration pathways, plus a cross-cutting Modeling and Assessment area, comprise the research and development portfolio of the program:

- **Separation and Capture** targets novel, low-cost approaches to removal of carbon or CO_2 from energy production and conversion systems.
- **Sequestration of CO_2 in Geologic Formations** assesses the applicability and effectiveness of long-term CO_2 storage in geologic structures such as oil and gas reservoirs, unmineable coal seams, and saline reservoirs.
- **Ocean Sequestration** examines potential mechanisms to enhance ocean storage of atmospheric CO_2 through processes to speed CO_2 uptake by the oceans or to inject CO_2 for deep ocean storage.
- **Carbon Sequestration in Terrestrial Ecosystems (forests, soils, and other vegetation)** examines the potential to enhance the natural terrestrial uptake and retention of atmospheric CO_2 through coupling improved agricultural and forestry processes with fossil energy production and use systems.
- **Advanced Concepts** examines novel approaches to chemical, biological, or other processes to recycle or reuse the CO_2 that is produced in energy systems.
- **Modeling and Assessments** provides the analysis to define and assess R&D opportunities within the five main research areas.

In these research areas, the program portfolio focuses on novel, breakthrough R&D. Specific near-term emphasis is being placed on three critically important components—capture, geologic sequestration, and the environmental acceptability of all the program pathways. Additional detail on these individual pathways can be found in the updated version of the FE *Carbon Sequestration Program Plan* which is expected later this year.

VII. PLANS AND ACTIVITIES

The program plans are based on two primary drivers. First, reducing the cost of sequestration can enable continued economic growth through affordable energy. Second, there is a time window over the next 15 years for R&D to work in developing the lower-cost technology options, because stabilization would not require large-scale deployment until 2015 and beyond. In the program portfolio, each project falls in a typical progression of R&D, where R&D stages are defined as :

Assessment: conceptual designs, modeling analysis
Conceptual R&D: experimental studies, prototype development
Bench-Scale Technology Development: laboratory experiments, systems integration
Field Testing: large-scale prototype development
Verification with Large Projects: testing and monitoring during operation over extended periods of time

The program's life cycle and the projected resource requirements to meet the program goals are shown in Figure 7. In all technology areas and all stages of R&D, the program seeks to both lower the cost of carbon sequestration and to clearly demonstrate its environmental acceptability.

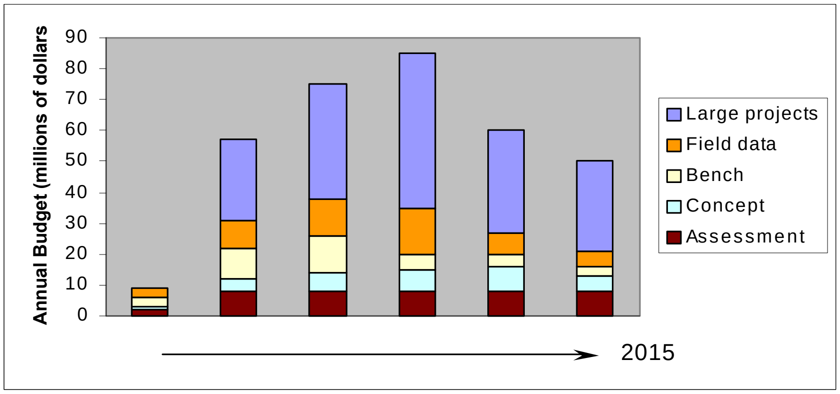

Figure 7. Program Life Cycle

A. The Path Forward

The program goals, benefits, strategy, and pathways have been described in the previous sections. The goals section lays out what must be accomplished. The benefits section demonstrates that time is critical in achieving maximum program benefits should policy actions directed at achieving stabilization be required in the future.

The potential scale of any future implementation to achieve stabilization is enormous. For example, under a scenario of stabilization at 550 ppm after improved energy supply and end-use efficiency options have been fully applied, the probable level of sequestration implementation necessary by 2020 is about 130 million tons of carbon per year. This is equivalent to the total CO_2 emissions from 40 500-MW coal-fired power plants, or some combination of those plus sources such as gas-fired power plants, gas processing plants, refineries, and others. By 2030 the requirement will have increased to 240 million tons/year and will continue to increase with economic growth.

A capability to achieve this scale of carbon sequestration implementation will require that a broad portfolio of low-cost, environmentally acceptable options be available, such that all regions of the country and sectors of the energy economy would have viable options from which to choose. Hence program implementation calls for parallel efforts in the various pathways.

Each pathway will have a different timeframe for achieving readiness for deployment, based upon the state of science and technology from which the program starts.

Figure 8 shows a summary of key milestone for the Sequestration Program over the next fifteen years. Milestones are presented for each of the program technology elements as well as for cross-cutting activities. There are differences among the time frames in which various milestones are planned to be achieved. This is due to the fact that some milestones represent opportunities that are adaptations of existing industrial practices (amine separation, enhanced oil recovery) or other research areas and are farther along the development path. Other milestones are associated with areas such as mineralization and biological and chemical conversion which are in the early stages of development. The advanced concepts milestones are based on the notion that in the future there will be increasing opportunities for identification of novel and advanced concepts by the research community. The program plans to evoke such concepts through periodic solicitations. Successful projects in the advanced concepts element will span the R&D spectrum from conceptualization through technology verification - a necessarily long process. The milestone schedules reflect an assessment, based on industry input, of the achievable time frames.

B. Current Activities

The program is currently funding or planning to fund a broad range of activities that support the early milestones in each of the technology thrust areas. Table 1 presents selected current activities being pursued by the program. Each activity is being undertaken because, if successful, it will contribute to achieving one or more of the milestones set forth in Figure 8. The current activities are organized by technology thrust area and categorized as assessment, exploratory and technology base research, or technology development.

Table 1 does not contain the results of a pending solicitation. In FY 1999, the program published a solicitation for cost-shared industry-led projects on "Research and Development of Technologies for the Management of Greenhouse Gases." The solicitation has two submission dates, January 18, 2000, and July 31, 2000. Award decisions on the January 18 submissions will be completed in sufficient time to enable proposers to revise or resubmit proposals to the second submission. No public statements can be made regarding any of the projects until the award process is completed, but it is safe to say that a significantly expanded slate of activities will be underway in the near future.

Progress Through Partnership

CO_2 capture and Geologic Sequestration: Progress through Partnership was a collaborative workshop held in September 1999 to create new solutions to the challenge of CO_2 capture and geologic sequestration. The workshop was jointly sponsored by the IEA/GHG, BP Amoco, and FE. It consisted of:

- International, national, and industry perspectives
- Panel discussions on CO_2 capture and geologic sequestration technologies
- Status reports from ongoing CO_2 sequestration projects
- Working sessions to develop an industry work program leading to breakthroughs in costs and performance

The partnership between the U.S. DOE, the IEA/GHG, and BP Amoco was successful in bringing together a diverse group of experts in CO_2 capture and geologic sequestration. Over 140 participants attended the workshop. Seventy-five percent of the participants were from industry, and 30% came from outside the United States. The workshop proceedings are available through the program contacts (see last page of this publication).

Figure 8. Carbon Sequestration R&D Program Milestone

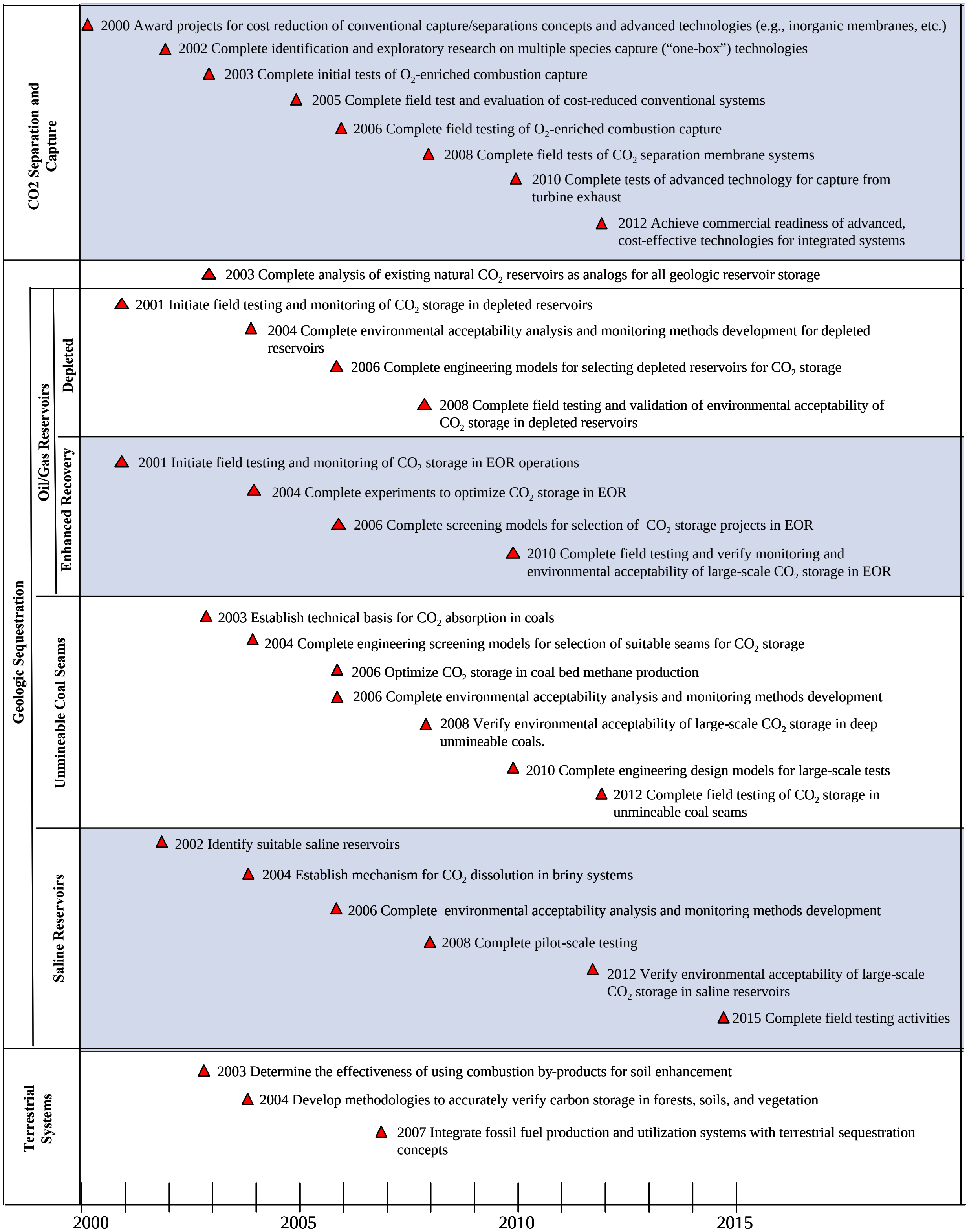

Figure 8. Carbon Sequestration R&D Program Milestone *(Continued)*

Ocean Sequestration

- 2001 Complete initial deep ocean injection experiment and design of next experiments
- 2003 Complete identification of comprehensive set of biomarkers to assess ecological implications of deep-ocean storage of CO_2
- 2004 Conduct second series of deep injection experiments
- 2006 Establish technical feasibility of deep ocean CO_2 injection and monitoring
- 2007 Establish key ecological factors for ocean storage of CO_2
- 2008 Field test large-scale application of nutrients and third series of deep injection experiments
- 2012 Data and analysis available for complete performance & environmental determination on ocean sequestration

Advanced Concepts

- 2000 Award Novel Concepts II exploratory research projects from FY 1999 solicitation
- 2001 Down select projects from FY 1998 Novel Concepts solicitation for Phase III field testing
- 2003 Select Novel Concepts II projects for engineering-scale development
- 2005 Award Novel Concepts III exploratory research projects from open solicitation
- 2007 Complete Field test and environmental validation of Novel Concepts I project(s)
- 2010 Award Novel Concepts IV exploratory research projects from open solicitation
- 2012 Complete Field test and environmental validation of Novel Concepts II projects
- 2015 Complete Field test and environmental validation of Novel Concepts III projects
- 2015 Award Novel Concepts IV projects

Cross-cutting Activities

NETL Sequestration Research Focus Area

- 2001 Establish research focus area at the NETL
- 2003 Produce comprehensive physical models on CO_2 flow in water/porous media
- 2004 Determine the global macro-economic implications of sequestration technologies
- 2006 Resolve technical issues associated with CO_2 storage in briny waters
- 2011 Establish synthetic routes to mimic natural carbonate precipitation in seawater
- 2013 Understand the environmental aspects of CO_2 sequestration in coal seams

IEA/GHG Programme

- 2000 Co-sponsor GHGT-5, an international conference on greenhouse gas emissions reduction technologies
- 2001 Complete Phase 3 of Assessments Program
- 2004 Complete Phase 4 of Assessments Program
- 2007 Complete Phase 5 of Assessments Program
- 2010 Complete Phase 6 of Assessments Program

Modeling & Assessment

- 2002 Complete Screening models for Novel Concepts
- 2004 Complete engineering and economic models for advanced conventional capture and separation systems
- 2005 Complete models for oil and gas reservoir storage
- 2008 Complete models for deep coal seams storage
- 2010 Complete models for deep saline reservoir storage
- 2012 Complete models for assessment of cost, performance, and environmental acceptability of deep ocean storage

2000 2005 2010 2015

Table 1. Examples of Current Activities of the Carbon Sequestration Program

	Assessment	Exploratory and Technology Base Research	Technology Development
CO_2 Separation and Capture	***Power Generation Models***–Evaluation tools for grass roots and retrofit power systems that are integrated with CO_2 separation and capture—enabling comparison of various options and identifying component R&D priorities. [SFA Pacific] ***Power plant retrofits***–Detailed cost analysis of three options for CO_2 capture and separation on an operating coal-fired power plant. [Combustion Engineering, Ohio Coal Development Office, American Electric Power]	***Vortex contactor***–Laboratory experiments on a vortex tube contactor, a new type of gas/liquid contactor, are being conducted. The vortex tube promises to cost 50% less than conventional packed-bed contactors for dilute CO_2 capture applications such as air combustion systems and gas processing plants. [INEEL, Purdue University, **Pacific Gas and Electric, Southern California Gas, BP Amoco**] ***Chemical sorbents***–New durable copper-based CO_2 sorbents, with high CO_2 selectivity and absorption capacity, are being developed. These sorbents could be used in fluidized bed applications. [TDA Research, Inc.] ***CO_2 Hydrates***–Laboratory testing to determine the feasibility of using pressurized, nucleated water to separate CO_2 and hydrogen in a coal gasification process. The CO_2 is selectively captured through the formation of icelike water/CO_2 hydrates. [**Bechtel**, LANL]	***Inorganic membranes***– Manufacturing techniques are being developed for a palladium-based membrane that reforms hydrocarbons while producing separate streams of hydrogen and CO_2. [Research Triangle Institute] ***Wet CO_2 Scrubbers***–Laboratory experiments aimed at improving the performance of wet CO_2 scrubbing by the addition of certain solvents and using advanced contacting methods. [NETL] ***Polymer membranes***–Structurally altered polymeric membranes are being developed and optimized for high-temperature operation (100-400ºC) to enhance integration with power generation and industrial systems [LANL]
Geologic Sequestration	***Enhanced Oil Recovery***–Evaluation of non-conventional approach of injecting CO_2 early in the productive life of oil reservoirs to increase both the amount of oil produced and the amount of CO_2 sequestered. [Advanced Resources International] ***Coal Bed Methane***– The mechanisms by which CO_2 displaces methane from the surface of various coals are being determined. [Oklahoma State University, Pennsylvania State University]	***Saline Formations***–Through modeling and laboratory experiments, evaluation criteria for determining optimum saline water-bearing reservoirs for long-term CO_2 storage have been developed. The criteria have been applied to 22 basins in the United States. [Battelle Memorial Institute, University of Texas] ***Coal Seams***–Techniques are being developed for measuring the sorption of CO_2 in coal seams with the goal of being better able to assess CO_2 sequestration potential. [NETL] ***A Broad 3-year Study***–A comprehensive program to evaluate the potential of geologic sequestration of CO_2 in formations such as brine reservoirs, depleted oil reservoirs, and coalbeds. [LBNL, LLNL, and ORNL, **Chevron, Texaco, Pan Canadian Resources, Shell CO_2 Co., BP-Amoco, Statoil**, Alberta Research Council Consortium]	***Environmental Impacts of CO_2 Injection***–Geophysical and geochemical techniques will be used to determine the fate and monitor the transport of CO_2 in a depleted oil reservoir. The data are necessary to properly evaluate the long-term environmental aspects of CO_2 sequestration in oil and gas reservoirs. [SNL, LANL, **Strata Production Company**, New Mexico Petroleum Recovery Center]
Terrestrial		***Soil enhancement***–Combining deep mulching of biomass (dead leaves and other detritus) with coal combustion by-products to increase the carbon uptake of marginally productive lands. Small-scale experiments, being conducted in the Savannah River Forest, will explore the use of coal combustion by-products to increase soil fertility. [**USFS**, ORNL, PNNL, Ohio State University, Virginia Polytechnic Institute]	

Table 1. Examples of Current Activities of the Carbon Sequestration Program *(Continued)*

	Assessment	Exploratory and Technology Base Research	Technology Development
Ocean Sequestration	***CO_2 Transport and Injection***– A feasibility study and engineering cost analysis of transport systems for deep ocean injection of liquid CO_2 to depths of 3,000 meters or more. The CO_2 would likely remain sequestered longer and potential environmental impacts would be significantly reduced if CO_2 is injected at 3,000 meters or more. Current technology would limit large-scale injection of CO_2 into the ocean to 1,300 meters. [**McDermott Technology Inc.**]	***Environmental Impacts***–Baseline data, including natural carbon and bio-activity background levels have been measured in preparation for a small-scale (40-60 metric tons) injection of CO_2 below the ocean surface (3,000 feet) off the coast of the island of Hawaii. Near-field diagnostic instruments and a remotely operated submersible vehicle will be used to monitor the dispersion of the injected CO_2. [Pacific International Center for High-Technology Research (PICHTR), Naval Research Laboratory, MIT, the University of Hawaii, and a number of international partners] ***CO_2 Hydrates***– Laboratory investigations on methods for CO_2 hydrates formation and determination of their physical and chemical properties. Following the laboratory studies, hydrate stability tests will be conducted on the ocean floor in Monterey Bay using remotely operated submersibles. [**USGS**, LLNL, **Monterey Bay Aquarium Research Institute (MBARI)**] ***Deep ocean simulation capability***–The fate of CO_2 in an ocean water column will be determined in a water tunnel. [NETL]	
Advanced Concepts		***Micro-algae (cyanobacteria)***–Films of tightly packed cyano-bacteria will be used to convert CO_2 to hydrocarbons via photosynthesis, enabling a much greater density of cyanobacteria in water thereby lowering systems cost. [INEEL, Memphis State University, University of Memphis]	***Landfill Gas***–Capturing methane formed during waste decomposition in landfills with gas-impermeable membranes. Two demonstration cells, each containing 9,000 tons of waste, are being used to evaluate this approach to reducing GHG emissions from landfills. [Institute for Environmental Management, Inc]
Cross-cut Activities	**A research focus area** is under way at NETL. In addition to conducting a portion of the Program's R&D portfolio with in-house NETL resources, the focus area will serve as a center of competence for the conduct of systems analysis on sequestration technology options. ***International Energy Agency, Greenhouse Gas R&D (IEA/GHG) Programme*** The IEA/GHG Programme is funded by the United States (via the Sequestration Program), 16 other countries, and several major corporations. It serves as an international nexus for thinking on carbon sequestration and other technologies as well as an effective forum for collaborative efforts among nations. The IEA/GHG Programme conducts an extensive agenda of studies and assessments as well as facilitating international cooperation on several R&D projects. ***Technology Transfer*** An analysis is examining expanded global markets for low-cost sequestration technologies.		

Even without projects from the pending solicitation, the program is currently funding a large number of high-quality cost-shared projects that represent a balanced portfolio of activities encompassing different technology areas and concepts in varying stages of development.

Consistent with feedback from industry and other stakeholders, the current activities are focused on two technology thrust areas; separation and capture, and geologic sequestration. Also, there are no Field Testing and Verification activities owing to the early stages of sequestration technology development.

The last row of Table 1 contains cross-cutting activities that involve two or more of the technology areas and contribute to the overall effort. In addition to the research focus area and the IEA/GHG Programme highlighted in the table, the program cosponsors and participates in a number of technical workshops and conferences. The recent strategy is to build on the initial broad-topic roadmapping exercises conducted at MIT and in conjunction with the Office of Science between 1995 and 1999 and sponsor more focused workshops on specific technology thrust areas. In FY 1999 the DOE, the IEA/GHG Programme, and BP Amoco collaborated to sponsor a workshop in carbon dioxide capture and geologic sequestration. Outreach activities are continuing in FY 2000 and include one workshop on advanced sequestration concepts in collaboration with Texas Utilities and the Los Alamos National Laboratory and another on sequestration in saline reservoirs in cooperation with IEA/GHG and industry.

VIII. Resource Requirements

Table 2 shows budget projections which have been built up from the estimated cost of the planned activities as identified in the outreach and technology roadmapping exercises conducted by the program. The resource requirements over 15 years are what is needed to achieve the program's goals.

Table 2. 15-year Resource Requirements for the Carbon Sequestration Program (millions)

2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
9.2	19.5	40	57	63	73	75	80	85	80	75	70	60	50	45	40

Figure 9 shows the projected funding profile over the period 2000-2015 to accomplish the program objectives previously defined. Program activities in the R&D spectrum–from assessments through verification of information in large projects are also indicated.

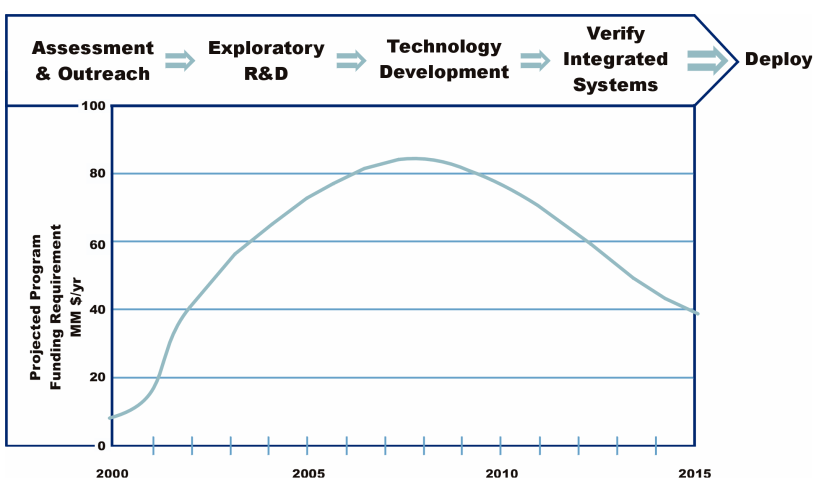

Figure 9. Program Funding Profile

For more information on the Carbon Sequestration Program please visit our web sites:

- DOE Carbon Sequestration Page @ http://www.fe.doe.gov/coal_power/sequestration/index.html
- NETL Carbon Sequestration Page @ http://www.netl.doe.gov/technologies

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