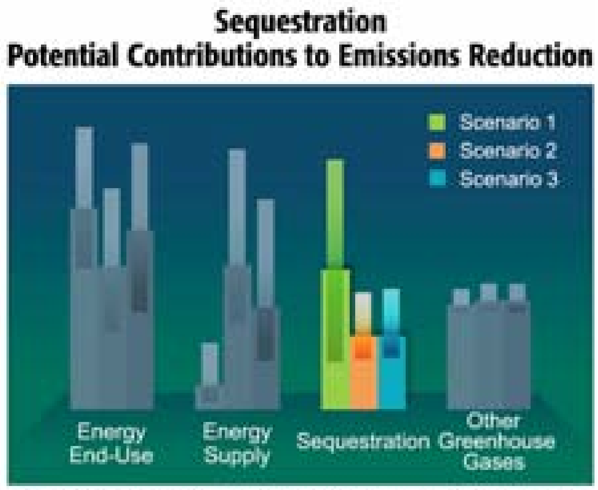
6 Capturing and Sequestering Carbon Dioxide

Technologies and improved management systems for carbon capture, storage, and sequestration can help to reduce carbon dioxide (CO_2) emissions and growth in atmospheric CO_2 concentrations. The main focus areas for research and development (R&D) related to carbon cycle management include (1) the capture of CO_2 emissions from large point sources, such as power plants, oil refineries, and industrial processes, and its storage in geologic formations or other storage media; (2) enhanced carbon uptake and storage by terrestrial biotic systems—terrestrial sequestration; and (3) improved understanding of the potential for ocean storage and sequestration methodologies.[1]



Potential contributions of Carbon Capture and Sequestration to cumulative GHG emissions reductions to 2100, across a range of uncertainties, for three advanced technology scenarios. See Chapter 3 for details.

If current world energy production and consumption patterns persist into the foreseeable future, fossil fuels will remain the mainstay of global energy production well into the 21st century. The Energy Information Administration (EIA) projects that by 2025 about 88 percent of global energy demand will be met by fossil fuels, because fossil fuels will likely continue to yield competitive advantages relative to other alternatives (EIA 2004a). In the United States, the use of fossil fuels in the electric power industry accounted for 39 percent of total energy-related CO_2 emissions in 2003, and this share is expected to slightly increase to 41 percent in 2025. In 2025, coal is projected to account for 50 percent of U.S. electricity generation and for an estimated 81 percent of electricity-generated CO_2 emissions. Natural gas is projected to account for 24 percent of electricity generation and about 15 percent of electricity-related CO_2 emissions in 2025 (EIA 2005).

Many scenarios of the future project that world coal markets will continue to grow steadily over the course of the 21st century, in the absence of CO_2 emissions restrictions. While increased energy efficiency, and use of renewable and nuclear energy afford good opportunities for reducing CO_2 emissions, fossil fuel reserves are abundant and economical, making their continued use an attractive option. In various advanced technology scenarios where CO_2 capture and storage technology were assumed to become a cost-competitive technology strategy, fossil-based energy continued to supply a large portion of total electricity consumed into the future (e.g., various studies estimated a 55-70 percent share), even under high carbon management requirements.

Human activities related to land conversion and agricultural practices have also contributed to the buildup of carbon dioxide to the atmosphere. During the past 150 years, land use and land-use changes were responsible for one-third of all human emissions of carbon dioxide (IPCC 2000). Over the next 100 years, global land-use change and deforestation are likely to account for at least 10 percent of overall human-caused CO_2 emissions. The dominant drivers of current and past land-use-related emissions of

---

[1] In this Plan, the three approaches are collectively referred to as "capturing and sequestering carbon dioxide" or "capturing and sequestering carbon."

CO_2 are the conversion of forest and grassland to crop and pastureland and the depletion of soil carbon through agricultural and other land-management practices (IPCC 2000). Past CO_2 emissions from land-use activities are potentially reversible, and improved land-management practices can actually restore depleted carbon stocks. Therefore, there are potentially large opportunities to increase terrestrial carbon sequestration.

The potential storage and sequestration capacity for CO_2 in various "sinks" is quite large. Some estimates indicate that about 83 to 131 gigatons of carbon (GtC) could be sequestered in forests and agricultural soils by 2050 (IPCC 2001b), while others estimate geologic storage capacities within a broad range of 300 to 3,200 GtC (IEA 1994a, 1994b, 2000). The ocean represents the largest potential sink for anthropogenic CO_2. The potential storage capacity of the ocean is largely unknown, although some researchers estimate that it might hold thousands of GtC or greater (Herzog 2001, Smith and Sandwell 1997, Hoffert et al. 2002).

There are potential ancillary benefits associated with carbon capture, storage, and sequestration. Many land-management practices that sequester carbon can improve water quality, reduce soil erosion, and benefit wildlife. The injection of CO_2 into geologic structures can be beneficially used to enhance recovery of oil from depleted oil reservoirs and the recovery of methane from unmineable coal seams.

Carbon capture, storage, and sequestration technologies have become a high priority R&D focus under CCTP because they hold the potential to reduce CO_2 emissions from point sources, as well as from the atmosphere, and to enable continued use of coal and other fossil fuels well into the future. Near-term R&D opportunities include optimizing carbon sequestration and management technologies and practices in terrestrial systems, and accelerating the development of technologies for capturing and geologically storing CO_2 for enhanced oil recovery. Longer-term R&D opportunities include further development of other types of geologic storage and terrestrial sequestration options, as well as furthering the understanding of both the role oceans might play in storing carbon and the potential unintended consequences of using the oceans for carbon sequestration.

The remaining sections in this chapter summarize the current and future research activities and challenges associated with developing carbon sequestration technology. In each section, the description of the current R&D activities includes a hyperlink to the CCTP report, *Technology Options in the Near and Long Term* (CCTP 2003).

6.1 Carbon Capture

Point source carbon dioxide emissions from power plants vary depending on the combustion fuel, technology, and operational use. Concentrating and capturing CO_2 from flue gas is a technological challenge. Flue gas from conventional coal-fired power plants contains 10 to 12 percent of CO_2 by volume, and flue gas from integrated gasification combined cycle (IGCC) plants contains between 5 and 15 percent CO_2. For a combined cycle gas turbine system, the CO_2 concentration is about 3 percent. The CO_2 in flue gases must be concentrated to greater than 90 percent for most storage, conversion, or reuse applications. Thus, R&D programs are targeted at capture systems that can produce a concentrated and pressurized stream of CO_2 at relatively low cost.

6.1.1 Potential Role of Technology

Large CO_2 point sources, such as power plants, oil refineries, and other industrial facilities are considered the most viable sites for carbon capture. The current technology for CO_2 capture uses a class of chemical absorbents called amines that remove CO_2 from the gas stream and produce byproduct food-grade CO_2 often used in carbonated soft drinks and other foods. However, the current absorbent process is costly and energy intensive, increasing the cost of a coal-fired plant by 50 to 80 percent (Davison et al. 2001) and energy reductions on the order of 30 percent of the net power generation rate (DOE 1999). Thus, several R&D opportunities are being pursued to reduce CO_2 capture costs and lessen the energy reductions in power generation, or the "net energy penalty."

6.1.2 Technology Strategy

Realizing the possibilities for point source CO_2 capture requires a research portfolio that covers a wide range of technology areas, including post-combustion capture, oxy-fuel combustion, and pre-combustion decarbonization. R&D investments in technologies that use pure oxygen during combustion, pre-combustion de-carbonization technologies, regenerable sorbents, advanced membranes, and hydrate formation can potentially reduce costs, as well as the net energy penalty. After component performance evaluations are completed, the next short-term step would be to conduct pilot scale and slip stream (i.e., diversion of a small stream from the total emissions of an existing plant) level testing of the most promising capture technologies. Larger or full-scale tests might be appropriate within the next few decades to demonstrate and have a suite of capture technologies available for deployment. Fully integrated capture and storage demonstration systems would help to enable commercial deployment to mitigate the financial and technical performance risks associated with any new technology that must maintain a high availability, such as required by the power generation sector.

6.1.3 Current Portfolio

The metrics and goals for CO_2 capture research are focused on reducing the cost and energy penalty, because analysis shows that CO_2 capture drives the cost of sequestration systems. Similarly, the goals and metrics for carbon storage and measurement and monitoring are focused on permanence and safety. All three research areas work toward the overarching program goal of 90 percent CO_2 capture, with 99 percent storage permanence at less than 20% increase in the cost of energy services by 2007, and less than 10 percent by 2012.

Across the current Federal portfolio, agency activities are focused on a wide range of technical issues. See Section 3.1.1 (CCTP 2005):
http://www.climatetechnology.gov/library/2005/tech-options/tor2005-311.pdf

New technologies to reduce the capital and energy penalty costs for post-combustion capture are currently under development and include regenerable sorbents, advanced membranes, and novel concepts such as forming CO_2 hydrates to facilitate capture. One such novel concept, the hydrate process, could be especially attractive for advanced coal conversion systems like the IGCC.

A challenge for post-combustion capture is the large amount of gas that must be processed per unit of CO_2 captured. This is especially true for combustion turbines where the concentration of CO_2 in the flue gas can be as low as 3 percent. One area of research is developing gas/liquid contactors where CO_2 gas is chemically absorbed into a liquid, and the resulting mixture is then separated.

Oxygen-fired combustion is also being researched to determine if CO_2 can be recovered in the combustion process. In oxygen-fired combustion, oxygen and recycled flue gas, instead of air, are used in combustion of petroleum coke, coal, or biomass fuels. Current R&D investments are also being made in low-cost oxygen separation technologies, such as oxygen transport membranes.

For new construction or re-powering of existing coal-fired power plants, several technology options can provide a pure stream of CO_2 at relatively low incremental cost. These processes are referred to as pre-combustion decarbonization, which results in concentrated streams of hydrogen and CO_2. In gasification, the hydrocarbon is partially oxidized, causing it to break up into hydrogen (H_2), carbon monoxide (CO), and CO_2, and possibly some methane and other light hydrocarbons. The CO can be reacted with water to form H_2 and CO_2, and the CO_2 and H_2 can be separated. The H_2 can be used in a combustion turbine or fuel cell, and the CO_2 can be stored.

A number of collaborative efforts are currently underway that will contribute to this strategy. Regional Carbon Sequestration Partnerships have been organized within the United States, and include networks of state agencies, universities, and private companies focused on determining suitable approaches for capturing and storing CO_2. Four Canadian Provinces are also participating. The Partnerships are developing a framework to identify, validate, and potentially test the carbon capture and storage technologies best suited for each geographic region and its point sources. During Phase II, beginning in 2005, the Partnerships will pursue technologies for small-scale sequestration validation testing.

The DOE Carbon Sequestration Program is participating in collaborations with international partners in developing new capture and sequestration technologies. Among these are a cooperative agreement with Canada (Weyburn Project – Box 6-1) and the Sleipner North Sea Project (Box 6-2).

Box 6-1

WEYBURN II CO_2 STORAGE PROJECT

DOE is participating in this commercial-scale project that is using CO_2 for enhanced oil recovery. CO_2 is being supplied to the oil field in southern Saskatchewan, Canada, via a 320 kilometer pipeline from a North Dakota coal gasification facility. The goal is to determine the performance and undertake a thorough risk assessment of CO_2 storage in conjunction with its use in enhanced oil recovery. The project will include extensive above and below ground CO_2 monitoring.

Box 6-2

Sleipner North Sea Project

Roughly one million metric tons per year of vented CO_2 from a natural gas platform in the North Sea is being captured and injected into the Utsira saline aquifer formation. The Sleipner Project was spearheaded by Statoil and began operation in 1996. DOE is providing research funding for measurement, verification and transport modeling activities to compliment and enhance the injection experiment.
(DOE/NETL 2004)

The Carbon Sequestration Leadership Forum (CSLF – Box 6.3) is an international collaborative effort to focus international attention on the development of carbon capture and storage technologies.

Box 6-3
Carbon Sequestration Leadership Forum (CSLF)

Established by the State Department and DOE in February 2003, the CSLF coordinates data gathering, R&D and joint projects to advance the development and deployment of geologic carbon sequestration technologies worldwide. The CSLF is a particularly attractive mechanism for achieving international cooperation for larger field tests. See http://fossil.energy.gov/programs/sequestration/cslf

6.1.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- Reduce the costs for sorbents, reducing regeneration energy requirements, and increasing sorbent life.

- Increase understanding of the CO_2 purity requirements to ensure that CO_2 transportation and storage operations are not compromised. Regarding CO_2 transportation, small quantities of SO_2 can lead to two-phase flow and pipeline pressure loss. The presence of water and other minute contaminants might promote acid formation and lead to pipeline and wellbore integrity problems. The history of transporting CO_2 in pipelines that contain substantial amounts of SO_x and NO_x is limited. These components can also impact the integrity of reservoir cap rock.

- Develop pre-and post-combustion CO_2 capture technologies that reduce the economic impacts of contaminants in a gas stream. For example, the corrosive nature of some of the contaminants can complicate CO_2 separation processes. Too much nitrogen in the CO_2 can significantly increase the cost of compression prior to geologic storage.

- Develop pre- and post-combustion CO_2 capture technologies that enable storage of criteria pollutants (SO_x, NO_x, H_2S) with the CO_2. In this area, the criteria pollutants are not separated from the CO_2 stream, but rather stored along with the CO_2.

- Continue to improve the cost-effectiveness of CO_2 separation membranes. Performance is improved by more cost-effective designs and materials with increased selectivity to CO_2 (increased CO_2 concentration per single membrane pass), increased throughput (increased flow rate per single membrane pass), and improved chemical stability (a measure of how well the membrane resists chemical reaction with its environment).

- Continue to lower the costs of oxygen used by coal-fueled power plants with separation technologies such as oxygen transport membranes. Success in this area is important to reducing the costs of oxy-combustion technologies (e.g., circulating fluidized bed designs), as well as gasification technologies.

- Develop an integrated modeling framework for evaluating alternative carbon capture technologies for existing and advanced electric power plants.

- Pursue innovative, potentially high-payoff concepts in areas such as advanced materials, and chemical and biological processes. Examples include ionic compound CO_2 solvents, novel microporous metal organic frameworks (MOFs) suitable for CO_2 separation and metabolic engineering to create strains of microbes that feed off CO_2 and produce useful chemical byproducts.

- Continue system integration and advancements of classical MEA-based systems for near-term carbon dioxide availability.

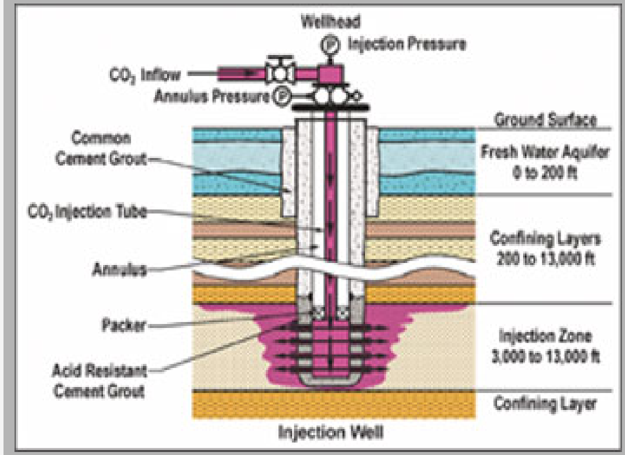
The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

6.2 Geologic Storage

Different types of geologic formations can store CO_2, including depleted oil reservoirs, depleted gas reservoirs, unmineable coal seams, saline formations, shale formations with high organic content, and others. Such formations have provided natural storage for crude oil, natural gas, brine, and CO_2 over millions of years. Each type of formation has its own mechanism for storing CO_2 and a resultant set of research priorities and opportunities. Many power plants and other large point sources of CO_2 emissions are located near geologic formations that are amenable to CO_2 storage. For example, DOE, along with private and public sector partners, is conducting research on the suitability of geologic formations at the Mountaineer Plant in West Virginia (Box 6-4).

Box 6-4

Carbon Sequestration Research at American Electric Power's Mountaineer Plant



American Electric Power's Mountaineer Plant in New Haven, West Virginia, is the site for a carbon sequestration research project funded by the U.S. Department of Energy and a consortium of public and private sector participants. The research will determine whether the geology near the Mountaineer Plant is suitable for injection of CO_2, where it can be absorbed and stored. If the site proves to be geologically sound for storage, the data collected during the study will be used to inform simulations, risk assessment and permit applications, and to design the monitoring plans for future applications.

The study is part of a \$4.2 million carbon sequestration research project led by Battelle Memorial Institute (in Columbus, Ohio). The project is managed by DOE's National Energy Technology Laboratory.

6.2.1 Potential Role of Technology

Geologic formations offer an attractive option for carbon storage. The formations are found throughout the United States, and there is extensive knowledge about many of them from the experience of exploration and operation of oil and gas production. Opportunities exist in the near term to combine CO_2 storage with enhanced oil recovery (EOR) and enhanced coal-bed methane (ECBM) recovery using injected CO_2. In 2000, 34 million tons of CO_2, roughly equivalent to annual emissions from 6 million cars, were injected as part of EOR activities in the United States.

Coal-bed methane has been one of the fastest growing sources of domestic natural gas supply. Pilot projects have demonstrated the value of CO_2 ECBM recovery as a way to increase production of this resource.

In the long term, CO_2 storage in saline and depleted gas formations is being explored. One project is currently in commercial operation, where one million tons of CO_2 per year are being injected in a saline formation at the Sleipner natural gas production field in the North Sea (see Box 6-2). The Frio Brine Pilot experiment near Houston, Texas, is the first U.S. field test to investigate the ability of saline formations to store greenhouse gases (GHGs). In October 2004, 1,600 tons of carbon dioxide was injected into a mile-deep well. Extensive methods were used to characterize the formation and monitor the movement of the carbon dioxide. The site is representative of a very large volume of the subsurface from coastal Alabama to Mexico and will provide experience useful in planning carbon dioxide storage in high-permeability sediments worldwide.

The overall estimated capacity of geologic formations appears to be large enough to store decades to centuries worth of carbon emissions, although the CO_2 storage potential of geologic reservoirs depends on many factors that are, as yet, poorly understood. For example, characteristics of reservoir integrity, volume, porosity, permeability, and pressure vary widely even within the same reservoir, making it difficult to establish a reservoir's storage potential with certainty. Assessments of storage capacity could help to better understand the potential of geologic formations for CO_2 storage.

6.2.2 Technology Strategy

Potential CO_2 sources and sinks vary widely across the United States, and the challenge is to understand the economic, health, safety, and environmental implications of potential large-scale geologic storage projects. The geologic storage program was initiated in 1997 and initially focused on smaller projects. However, field testing is necessary to verify the results of smaller-scale R&D, and the program is taking on larger projects, as knowledge grows and opportunities and funding become available.

In the near-term, activities will focus on addressing important carbon storage-related issues consistent with the *Carbon Sequestration Technology Roadmap and Program Plan* (DOE 2005). Among these activities are developing an understanding of the behavior of CO_2 when stored in geologic formations. Long-term activities will be needed in the areas of understanding and reducing potential health, safety, environmental, and economic risks associated with geologic sequestration.

Regional domestic partnerships and international cooperation are viewed as key to deploying carbon storage technologies. Field validation activities are needed to test the large-scale viability of point-source capture and storage systems and demonstrate to interested parties the potential of these systems.

6.2.3 Current Portfolio

The goal of geologic storage R&D portfolio is to develop domestic CO_2 underground storage repositories capable of accepting around a billion tons of CO_2 per year. Toward this goal, there is a need to demonstrate that CO_2 storage underground is safe and environmentally acceptable, and an acceptable GHG mitigation approach. Another need is to demonstrate an effective business model for CO_2 enhanced oil recovery and enhanced coalbed methane, where significantly more CO_2 is stored for the long term than under current practices.

The Federal portfolio for geologic storage activities includes several major thrusts designed to move technologies from early R&D to deployment. See Section 3.1.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-312.pdf

Core RD&D focuses on understanding the behavior of CO_2 when stored in geologic formations. For example, studies are being conducted to determine the extent to which CO_2 moves within the geologic formation, and what physical and chemical changes occur to the formation when CO_2 is injected. This information is needed to ensure that CO_2 storage will not impair the geologic integrity of an underground formation and that CO_2 storage is secure and environmentally acceptable. There are three major research thrusts:

- **Knowledge Base and Technology for CO_2 Storage Reservoirs**. These activities seek to increase the knowledge base and technology options. The petroleum industry has built significant experience over the past few decades on how to inject carbon dioxide into oil reservoirs for EOR. Many of the issues related to injection technologies and gas compression have already been solved. Because oil and gas reservoirs have been able to store gases and other hydrocarbons for geologically significant periods of time (hundreds of thousands to millions of years), they likely have caprocks that will be good seals for CO_2 as well. Furthermore, CO_2 can potentially enhance oil and gas production, which can help mitigate carbon storage costs. However, because the petroleum industry understandably has been focused on resource recovery and not on CO_2 storage, it has not developed procedures to maximize the amount of CO_2 that is stored or to track the CO_2 once it is has been injected to ensure that it remains in the ground. In addition, most well-developed oil fields, by definition, contain many wells that have pierced the caprock for the field, creating potential leakage pathways for CO_2. Research is currently underway to develop technologies to locate abandoned wells, to track the movement of CO_2 in the ground, and to ensure long-term storage, as well as to optimize costs, assess performance, and reduce uncertainties in capacity estimates.

  Another attractive option is carbon storage in deep, unmineable coal seams. Not only do these formations have high potential for adsorbing CO_2 on coal surfaces, but the injected CO_2 can displace adsorbed methane, thus producing a valuable byproduct and decreasing the overall storage cost. One potential barrier is the tendency of coal to swell in volume when adsorbing CO_2. This can cause a sharp drop in permeability, thereby impeding the flow of CO_2 and the recovery of methane. Laboratory, modeling and field studies are currently being implemented and proposed to gain a better understanding of the processes behind coal swelling and determine if it will be a significant barrier to sequestration in coal seams.

  Another option is the use of large saline formations for CO_2 storage, a relatively new concept. About two-thirds of the United States is underlain by deep saline formations that have significant sequestration potential. Since the water in the saline formations is typically not suitable for irrigation or consumption, many opportunities exist for CO_2 to be injected without adverse impacts. The storage capacity of saline formations is enhanced because of the ability of CO_2 to dissolve in the aqueous phase. But, there are uncertainties associated with the heterogeneous reactions that may occur between CO_2, brine, and minerals in the surrounding strata, especially with respect to reaction kinetics. For example, saline formations contain minerals that could react with injected CO_2 to form solid carbonates, which would eliminate potential migration out of the reservoir. On the negative side, the carbonates could plug the formation in the immediate vicinity of the injection well. Researchers are looking into multiphase behavior of CO_2 in saline aquifers and the volume, fate, and transport of the stored CO_2. New technologies and techniques are being developed to reduce cost and inefficiency due to leaks and to better define the geology of the saline aquifers. A recent review article addresses the technological challenges of sequestering carbon dioxide in saline formations and coal seams (White et al. 2003). For more information, see Section 3.1.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-312.pdf

- **Measurement and Monitoring**. These activities are described more fully in Chapter 8. An important R&D need is to develop a comprehensive monitoring and modeling capability that not only focuses on technical issues, but also can help ensure that geologic storage of CO_2 is safe. Long-term geologic storage issues, such as leakage of CO_2 through old well bores, faults, seals, or diffusion out of the formation, need to be addressed. Many tools exist or are being developed for monitoring geologic storage of CO_2, including well testing and pressure monitoring; tracers and chemical sampling; surface and borehole seismic monitoring; and electromagnetic/geomechanical meters, such as tiltmeters. However, the spatial and temporal resolution of these methods may not be sufficient for performance confirmation and leak detection.

- **Health, Safety, and Environmental Risk Assessment**. Assessing the risks of CO_2 release from geologic storage sites is fundamentally different from assessing risks associated with hazardous materials, for which best practice manuals are often available. In some cases, geologic storage sites may exist near populated areas. Although CO_2 is not toxic or flammable, it can cause suffocation if present at high concentrations. Therefore, the mechanism for potential leaks must be better understood. The assessment of risks includes identifying potential subsurface leakage modes, the likelihood of an actual leak, leak rate over time, and the long-term implications for safe carbon storage. Diagnostic options need to be developed for assessing leakage potential on a quantitative basis.

Two activities cited in Section cited in Section 6.1.3 will continue to play an important role in encouraging the deployment of technologies developed under the core RD&D program. The Regional Partnerships Program[2] is building a nationwide network of Federal, State, and private sector partnerships to determine the most suitable technologies, regulations, and infrastructure for future point source carbon capture, storage, and geologic sequestration in different areas of the country. The Carbon Sequestration Leadership Forum is facilitating the development and worldwide deployment of technologies for separation, capture, transportation, and long-term storage of CO_2.

In addition, the FutureGen project (Box 6-5) is expected to be the world's first coal-fueled prototype power plant that will incorporate geological storage. It will provide a way to demonstrate some of the key technologies developed with Federal support, and demonstrate to the public and regulators the viability of large-scale carbon storage.

---

[2] For more information on the Regional Partnerships Program, see http://fossil.energy.gov/programs/sequestration/partnerships.

6.2.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- Defining the factors that determine the optimum conditions for sequestration in geological formations, such as depleting oil and gas reservoirs, saline formations, and coal seams, as well as unconventional hydrocarbon bearing formations.
- Developing the ability to predict and optimize CO_2 storage capacity and resource recovery.
- Developing the ability to track the fate and transport of injected CO_2 in different formations. This includes applying surface and near-surface monitoring techniques such as surface CO_2 flux detectors, injecting tracers in soil-gas, and measuring changes in shallow aquifer chemistry for CO_2 leakage.
- Developing models to simulate the migration of CO_2 throughout the subsurface and the effects of injection on the integrity of caprock structures.
- Understanding geochemical reactions (see Box 6-6) and harnessing them to enhance containment.
- Developing injection practices that preserve cap integrity, and practices to mitigate leakage to the atmosphere.
- Developing an understanding of CO_2 reactions and movement in shales and other unconventional hydrocarbon-bearing formations that will permit the economic recovery of these hydrocarbons.
- Taking advantage of geologic differences in various regions by developing cost-effective systems to integrate energy conversion with carbon capture, geologic storage, and subsurface conversion of CO_2 into benign materials or useful byproducts (e.g., through biogeochemical processes that can create methane or carbonates).
- Developing improved methods and data for estimating the overall costs of geologic sequestration, including capture, compression, and transportation.

Box 6-5

Future Gen

FutureGen is a public-private initiative to build the world's first integrated carbon capture/storage and hydrogen production power plant. When in operation, the prototype will be the cleanest fossil fuel power plant in the world. The plant will be a "living prototype" with future technological innovations incorporated into the design as they develop. An industrial consortium representing the U.S. coal and power industry will work closely with DOE to implement this project. Other countries have been invited to participate via the Carbon Sequestration Leadership Forum. See: http://www.netl.doe.gov/coalpower/sequestration/futureGen/main.html

- Economics of geologic sequestration.

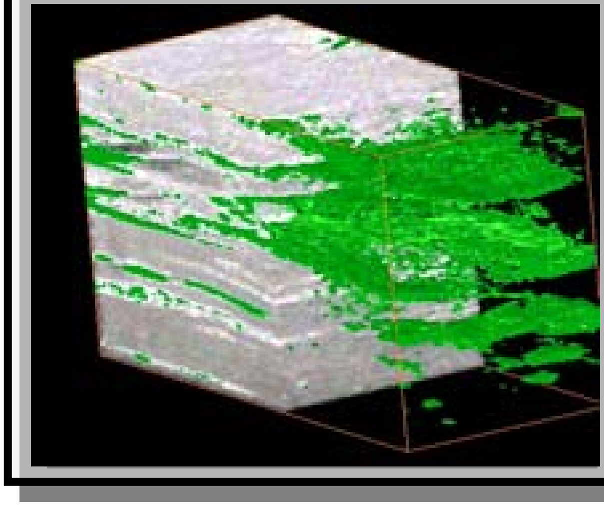
Pursuit of breakthrough concepts may be important for reaching long-term program goals. Breakthrough concepts R&D is pursuing revolutionary and transformational approaches with potential for low cost, permanence and large global capacity. For example, some of the lowest cost estimates for capture/sequestration options are for systems where flue gas components from coal-fueled plants are not scrubbed but rather stored in geologic formations with CO_2. This eliminates the need for costly flue gas cleanup systems, but the potential effects of this option are unknown. Technological innovations could come from concepts associated with areas not normally related to traditional energy R&D fields.

In the long term, CO_2 capture can be integrated with geologic storage and/or conversion. Many CO_2 conversion reactions are attractive, but too slow for economic chemical processes. Use of impurities in captured CO_2 (e.g., SO_x and NO_x) or additives could possibly enhance geologic storage and provide an opportunity to combine CO_2 emissions reduction with criteria pollutant emissions reduction.

Box 6-6

CO_2-Coal Interactions

Understanding the interactions between carbon dioxide and coal is one challenge that must be met before large-scale sequestration in coal seams will occur. Coal appears to swell in the presence of CO_2 under pressures found in deep unmineable coal seams. Laboratory studies and field trials are underway to determine how coal swelling occurs and whether CO_2 injectivity can be held high enough in the presence of swelling.



Field tests will be needed to verify R&D results. It is anticipated that many of these tests will eventually be carried out through the Regional Partnerships Program based on analysis of CO_2 sources and sinks by participants to determine the highest benefit projects.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

6.3 Terrestrial Sequestration

Terrestrial sequestration can play a significant role in addressing the increase of CO_2 in the atmosphere. A wide range of technologies and practices, including tree planting, forest management, and conservation tillage practices are available to increase the sequestration of carbon in plants and soils. Terrestrial sequestration activities can provide a positive force for improving landscape-level land management and provide significant additional benefits to society, such as improvements in wildlife and fisheries habitat, enhanced soil productivity, reduction in soil erosion, and improved water quality. Terrestrial sequestration represents a set of technically and commercially viable technologies that have the capability to reduce the rate of CO_2 increase in the atmosphere. Given the size and productivity of the U.S. land base, terrestrial sequestration has distinct economic and environmental advantages. Globally, the potential for terrestrial sequestration is also significant, due in part to low-cost opportunities to reduce ongoing emissions from current land-use practices and land conversion and to enhance carbon stocks via afforestation, forest restoration, and improved forest and agricultural management.

Terrestrial sequestration technologies refer broadly to equipment, processes, decision tools, management systems and practices, and techniques that can enhance carbon stocks in soils, biomass, and wood products, while reducing CO_2 concentrations in the atmosphere. Extensions of terrestrial sequestration can use sustainably generated biomass to displace fossil fuels. Examples of terrestrial sequestration technologies include conservation tillage, conservation set-asides, cover crops, buffer strips, biomass energy crops, active forest management, active wildlife habitat management, low-impact harvesting, precision use of advanced information technologies, genetically improved stock, wood products life-cycle management, and advanced bioproducts.

6.3.1 Potential Role of Technology

Increasing terrestrial carbon stocks is attractive because it can potentially offset a major fraction of emissions, and serve as a bridge over an interim period, allowing for development of other low-CO_2 or CO_2-free technologies. Carbon stock management technologies and practices that enhance soil and forest carbon sinks need to be maintained once the carbon stock reaches higher levels. Although the benefits can be temporarily reversed by fire, plowing of cropland soils, and other disturbances, the potential improvements in carbon stocks are of such magnitude that they can play a significant overall role in addressing the increase in atmospheric CO_2 emissions from the United States and globally throughout the 21st century.

Other opportunities described in this section can provide benefits essentially indefinitely. For example, changes in crop management practices can reduce annual emissions of trace GHGs; sustainable biomass energy systems can displace fossil fuels and provide indefinite net CO_2 emissions reductions; and enhanced forest management and conversion to durable wood products provide a mechanism to allow forests to continually sequester carbon.

Estimates of the global potential for terrestrial sequestration activities remain uncertain. Such estimates are generally of the technical potential (i.e., the biophysical potential of managed ecosystems to sequester carbon), and disregard market and policy considerations. The IPCC (IPCC 2001c) estimates such technical potential of biological mitigation options (i.e., forest, agricultural, and other land-management activities) to be on the order of 100 GtC cumulative by 2050, at costs ranging from about $0.1 to about $20/t carbon in tropical countries, and from $20/t carbon to $100/t in non-tropical countries. Technical potential estimates for the United States range widely, depending on assumptions about biophysical sequestration rates per hectare, the land area available for different activities, and other factors. Widely cited estimates of U.S. technical potential for carbon sequestration include about 55-164 teragrams of carbon (TgC) per year for potential sequestration on croplands (Lal et al. 1998); 29-110 TgC per year on grazing lands (Follett et al. 2001); 210 TgC per year on forest land (Joyce and Birdsey 2000); and 91-152 TgC per year on dedicated bioenergy croplands (Tuskan and Walsh 2001). In addition, dedicated bioenergy crops would substitute for fossil fuels, leading to an estimated 450 Tg C reduction of CO_2 emissions (Tuskan and Walsh 2001). These estimates generally represent technical potential that does not reflect barriers to implementation, competition across land uses and sectors, or landowner response to public policies and economic incentives. A recent study of cropland (Eve et al. 2002) indicates a potential of about 66 TgC per year on croplands, toward the lower end of the Lal et al. (1998) range.

With regard to bioenergy, a recent DOE/USDA analysis estimates that U.S. forest and agricultural lands could sustainably supply up to 1,300 Tg of biomass/year for bioenergy, similar to the findings of Tuskan and Walsh, but without major shifts in land use or food or fiber production (Perlack et al. 2005). Such a quantity of biomass could displace over 30 percent of current U.S. petroleum consumption.

6.3.2 Technology Strategy

Realizing the opportunities to sequester carbon in terrestrial systems will require managing resources in new ways that integrate crosscutting technologies and practices. A balanced portfolio is needed that supports basic science, technological development, emerging technology demonstrations, innovative partnerships with the private sector, and techniques and metrics for measuring success.

An array of actual and potential technologies can be found in the short, mid, and long terms. In the short term, some technologies and practices being routinely used can be expanded to increase carbon sequestration. In addition, improvements to many current systems are needed to enable them to enhance above- and below-ground carbon stocks, and manage wood products pools. In the mid to long term, research can focus on options that take advantage of entirely new technologies and practices.

In the near- and long-term, the R&D portfolio needs include:

- Design, develop and demonstrate carbon management strategies consistent with economic and environmental goals for terrestrial ecosystems.
- Improve the understanding of the relationship of carbon management and ecosystem good and services.
- Determine how terrestrial systems' capacities can be manipulated to enhance carbon sequestration in time and space.
- Analyze the relationship between natural resource and agricultural policy, and terrestrial sequestration technologies and identifying ways to maximize synergies and avoid potential conflicts between the two.
- Evaluate existing and new market-based adoption and diffusion strategies for terrestrial sequestration technologies.
- Optimize management practices and techniques, accounting for all GHGs and their effects.
- Improve methods of measuring changes in carbon pools and verifying sequestration rates.
- Develop and analyze incentives for implementation.

6.3.3 Current Portfolio

Much of the research currently underway that could have applications for increasing terrestrial carbon sequestration is being undertaken for multiple reasons, often unrelated to climate change. Significant investments are being made in developing sustainable natural resource management systems that provide economic and environmental benefits. In particular, advances have been made in increasing forest productivity, effective and environmentally sound uses of crop fertilizers, enhancing soil quality, and in producing biomass feedstocks (see Figure 6-1).

Figure 6-1. Terrestrial Sequestration: Short Rotation Woody Crops, Soil, and Wood Products

Across the current Federal portfolio of terrestrial sequestration-related RD&D, multi-agency activities are focused on a wide range of issues, including the following:

- Cropland management and precision agriculture that can increase the amount of carbon stored in agricultural soils by increasing plant biomass inputs or reducing the rate of loss of soil organic matter to the atmosphere. The goals of this activity are to quantify the carbon sequestration potential of agricultural practices for various climates and soils; develop the combination of practices (e.g., plant species, siting, establishment practices) that optimize carbon sequestration and minimize production losses for various types of agricultural practices; and develop decision support tools for farmers, other land managers, and policy makers to inform agricultural policy decisions of the relative costs and benefits of different cropland management approaches, both in terms of carbon sequestration and production. See Section 3.2.1.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3211.pdf

- Conversion of marginal croplands to other less-intensive land uses to conserve reserves and buffer areas. The goals of this activity are to quantify the carbon sequestration potential of cropland conservation programs for various climates and soils; develop the combination of practices (e.g., plant species, siting, establishment practices) that optimize carbon sequestration and minimize production losses for various types of cropland conservation practices; and develop decision support tools for farmers, other land managers, and policy makers to inform cropland conservation policies and the relative costs and benefits of different cropland conservation approaches, both in terms of carbon sequestration and production. See Section 3.2.1.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3212.pdf

- Evaluation of advanced forest and wood products management that may offer significant carbon sequestration opportunities. The goals and milestones of this activity are to increase energy efficiency of forest operations; develop and apply models to better understand the economics of achieving certain GHG mitigation goals through improved forest management; sensors/monitors and information management systems; advanced fertilizers, technologies, and application strategies to improve fertilizer efficiency and reduce nitrogen fertilizer inputs; integrated management strategies and systems to increase nutrient and water use efficiency, increase CO_2 uptake and sequestration and reduce emissions.; and wood product management and substitution strategies. The milestones are to have initial systems models and prototype operation on major plantation types in place by 2007. Also, to deploy first-generation integrated system models and technology by 2010. See Section 3.2.1.3 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3213.pdf

- Grazing management to increase amount of carbon in soils. The goals of this activity are to construct quantitative models that describe site-specific interactions among grazing systems, vegetation, soil and climate, and the effects on greenhouse gas dynamics; and to develop decision support tools to inform the relative costs and benefits of different grassland management scenarios for carbon sequestration and other conservation benefits. See Section 3.2.1.4 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3214.pdf

- Restoration of degraded rangelands using low-cost, reliable technologies. The goals of this activity are to develop low-cost, reliable technologies for the restoration of vegetation on degraded arid and semi-arid rangelands; improve decision support for the application of low-cost technologies, such as fire, to control invasive species and to reduce greenhouse gas emissions from mesic rangelands; and to develop seed production technology to produce low-cost seeds for reestablishing desired rangeland species. Currently costs are high and seed supply is limited for many cultivars. See Section 3.2.1.5 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3215.pdf

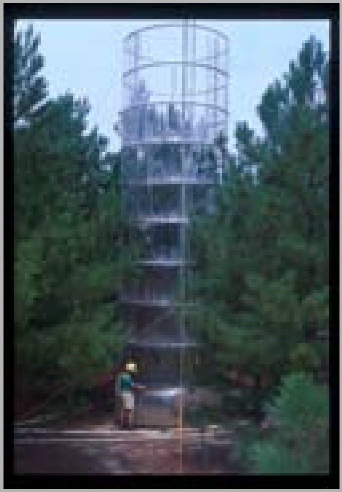
- Wetland restoration and management for carbon sequestration and GHG offsets. The goals of this activity are to evaluate various management practices on restored wetlands; delineate and quantify carbon stocks in U.S. wetlands by region and type; develop and demonstrate integrated management strategies for wetland carbon sequestration; and identify wetland areas most likely to be impacted by climate change and prioritize areas for protection. See Section 3.2.1.6 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3216.pdf

- Reclamation of mined lands using grassland, cropland, and forest restoration practices. The goals of this activity are to quantify carbon sequestration on reclaimed mined lands and evaluate the extent to which various management practices on reclaimed mined lands enhance carbon sequestration (i.e., measure the effects of organic and inorganic residues, grazing, plant biodiversity. See Section 3.2.1.7 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3217.pdf

- Use of biotechnology for modifying the chemical composition of plants and microorganisms to enhance carbon sequestration (see Box 6.7). The goals of this activity are to identify the traits needed in plants and microorganisms to increase soil carbon sequestration capacity; determine the feasibility of using biotechnology to modify the traits of plants and microorganisms that can affect soil carbon sequestration; develop systems for monitoring non-target environmental affects associated with plant modifications; develop methods to incorporate genetically modified plant and microorganisms into cropland and conservation reserve and buffers systems. See Section 3.2.2.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3221.pdf

Box 6-7

Physiological Mechanisms of Growth, Response and Adaptation in Forest Trees



Enhancing the natural capacity of terrestrial ecosystems to store carbon is a viable strategy for stabilizing rising CO_2 concentrations in the atmosphere. However, gains in improving the sequestration potential of croplands, grasslands, and forest lands could be enhanced by major scientific advancements in understanding the processes that control the initial uptake, ultimate chemical forms, and subsequent carbon transfer in plants and soils.

Research carried out by the U.S. Department of Agriculture and the U.S. Department of Energy is underway to determine the mechanisms that control the quantity and quality of carbon allocated to stems, branches, leaves, and roots of trees as a means of understanding the biological processes that underlie carbon sequestration in trees and soils; understanding controlling genetic mechanisms; and selecting, testing, and demonstrating useful genotypes. Research is focused on several species, including hybrid poplar, willow, and loblolly pine. The studies are designed to determine the interaction of physiological and biogeochemical processes and water and nutrient management on carbon fixation, allocation, storage, and dynamics in forest systems. Field and laboratory studies are being used to quantify and understand carbon dynamics, both above and below ground. Forest researchers hope that these and similar studies will provide the scientific foundation for managing forest systems to enhance carbon sequestration, and improve environmental quality and productivity.

- Terrestrial sensors, measurements, and modeling. The goals of this activity are to develop a new generation of sensors, probes, and other instruments to measure soil carbon, GHGs flux in situ across a wide variety of agricultural ecosystems. See Section 3.2.3.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3231.pdf

- Measuring, monitoring, and verification for forests. The goals of this activity are to develop technologies remote sensing data collection and analysis, in situ instrumentation and monitoring systems, and other measuring and monitoring technologies. See Section 3.2.3.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-3232.pdf

6.3.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- Quantifying the carbon sequestration potential for management practices and techniques across all major land uses, including cropland, forests, grasslands, rangelands, and wetlands; across cultivation and management systems; and across regions.

- Designing, developing, and testing management systems to increase carbon sequestration, maintain storage, and minimize net GHG emissions while meeting economic (i.e., forest and agricultural production) and environmental goals.

- Developing bioenergy and additional durable uses of bio-based products and improve management of residues and wood products.

- Improving biomass supply technologies (harvesting, handling, onsite separation and processing, transportation) to reduce costs and impacts; and enhance techniques that improve yields, transport, and efficiency of conversion to fuels.

- Exploring the use of trees and other vegetative cover in urban environments to both sequester carbon and reduce the urban heat island effect.

- Evaluating terrestrial carbon stock vulnerabilities and stability.

- Improving the understanding of the implications of potential sequestration options on the emissions of other GHGs through comprehensive accounting of all GHG emissions and sinks as land-based carbon sequestration technologies are implemented.

- Improving the performance of technologies and practices to provide additional benefits, including improvements in wildlife habitat; water and air quality; and soil characteristics such as stability, water infiltration and retention, and nutrient retention.

- Enhancing sequestration potential through the use of advanced technologies, including biotechnology techniques to enhance seed stock qualities, precision water and nutrient application, land management using geographic information system and other tools, and alternative tillage and harvest techniques.

- Developing novel alternative technologies such as high-lignin trees for combustion and low-lignin trees to reduce paper processing costs and improved digestibility of fodder and forage.

- Researching biotechnology (genomics, genetics, proteomics), and in managing biological and ecological processes affecting carbon allocation, storage, and system capacity that may aid in managing carbon. Improved understanding of the functional genomics of high-potential biomass crops can increase yields and provide a more effective basis for increasing the conversion efficiency of biomass of fuels, chemicals, and other bioproducts.

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

6.4 Ocean Sequestration

Because of the large CO_2 storage capacity of the ocean, increasing the carbon uptake and storage of carbon in the oceans has generated some interest. To understand the role the ocean could play, several issues must be addressed, including the *capacity* of the ocean to sequester CO_2, its *effectiveness* at reducing atmospheric CO_2 levels, the *depth and form* (liquid) for introduction of the CO_2 stream, and the *potential for adverse environmental consequences*. Ocean storage has not yet been deployed or thoroughly tested, but there have been small-scale field experiments and 25 years of theoretical, laboratory, and modeling studies of intentional ocean storage of CO_2. Nevertheless, little is known about the potential environmental consequences to ocean ecosystems and natural biogeochemical cycles.

Two strategies are typically considered for ocean carbon sequestration: (1) direct injection of a relatively pure stream of CO_2 into the ocean interior, and (2) iron fertilization to enhance the ocean's natural biological pump. It is generally thought that direct injection of CO_2 would be technically feasible and effectively isolate CO_2 from the atmosphere for at least several centuries, and the primary concerns relate to possible adverse environmental effects. In contrast, the technical feasibility and effectiveness of ocean fertilization remain open to question; furthermore, whereas direct injection approaches seek to minimize ecosystem impacts, ocean fertilization depends upon our ability to manipulate ecosystem function over large areas of the ocean.

Various observations indicate that the oceans take up (net) about 2 GtC/year or about one-third of the global emissions, and ultimately, over the period of centuries, oceans may take up about 70 percent of global fossil carbon emissions as carbon is transported across the ocean thermocline and mixed with deep ocean waters (IPCC 2001a). Ocean carbon sequestration strategies seek to increase the deep ocean inventory of CO_2. Intentional ocean storage of CO_2 could slow the increase of CO_2 in the atmosphere. After some time, injected CO_2 would be distributed widely in the oceans.

The volume of the ocean is very large relative to the size of fossil-fuel resources; thus, ocean carbon storage is not limited by physical capacity. The two factors that have the greatest potential to limit the available capacity of the ocean are (i) the goal for long-term equilibrium atmospheric CO_2 concentration and (ii) adverse environmental consequences. All CO_2 placed in the ocean will eventually interact with the atmosphere, adding some part of that CO_2 to the atmospheric burden. For example, injection of about 8000 Gt CO_2 to the deep ocean will eventually produce atmospheric CO_2 concentrations of about 750 ppm, even in the absence of additional CO_2 release to the atmosphere. It has been shown in experiments that high concentrations of CO_2 can harm marine organisms, but the effects of long-term exposure to relatively small additions of CO_2 are unknown.

6.4.1 Potential Role of Technology

Ocean sequestration offers the potential to reduce the level of CO_2 concentrations in the atmosphere. Under the direct injection approach, CO_2 would be captured from large point sources, e.g., fossil-fired power plants, industrial processes, etc., and then pressurized and injected at depths of 2,000 to

3,000 meters below surface, where it would be expected to remain for centuries. However, it has yet to be tested or deployed in a continuous mode at industrial concentrations.

Fertilization of the oceans with iron, a nutrient required by phytoplankton, is a strategy being considered to enhance the draw-down of CO_2 from the atmosphere and to accelerate the biological carbon pump. Iron fertilization is intended to promote carbon fixation by phytoplankton (primary production) leading to the sinking of some of this carbon to the deep ocean, where some of it will be oxidized back into carbon dioxide. Thus ocean fertilization will directly affect surface ocean ecosystems and expose deep-sea ecosystems to long-term, but relatively small, increases in CO_2 concentrations. Direct injection is likely to produce acute effects in the local region of injection, whereas fertilization would produce ecosystem shifts over large areas of the surface ocean.

6.4.2 Technology Strategy

To adequately assess the potential of ocean-based options as mitigation strategies, the potential adverse impacts on the ocean biosphere and the potential effectiveness must be evaluated and specific R&D criteria need to be addressed. A research portfolio is required that seeks to determine, via experimentation and computer simulations, the potential for storing anthropogenic CO_2 in the world's oceans while minimizing negative environmental consequences.

A variety of studies based on models and ocean observations indicate that the isolation of carbon from the atmosphere generally increases with the depth of injection (or oxidation of organic carbon). In the near term, the key research questions related to direct injection involve evaluating the impact of added CO_2 and/or nutrients on marine ecosystems and the biogeochemical cycles to which they contribute. This is being investigated through both observations and modeling of marine organisms and ecosystems, as is now being funded by DOE and the National Science Foundation (NSF), among others. In the long-term, the most important R&D activities need to focus on improving an understanding of the effects of elevated concentrations of CO_2 on marine organisms and ecosystems.

Near-term research needs related to iron fertilization are associated with understanding the magnitude of carbon export down through the water column and the effects of growth of harmful phytoplankton or diatom species. In the long-term, more emphasis is needed on understanding the effectiveness and environmental and ecological consequences of this approach.

6.4.3 Current Portfolio

Ongoing research activities target ocean carbon sequestration using direct injection and iron fertilization. These activities are summarized below:

- **Direct Injection**. Currently, the technology exists for the direct injection of CO_2. Previous laboratory experiments concentrated on establishing an understanding of the processes that occur when CO_2 comes into contact with high pressure seawater. As a result, a much better understanding of the influence of CO_2 hydrates (or clathrates) on the dissolution processes exists. Additional research conducted by DOE's Oak Ridge National Laboratory simulated a negatively buoyant clathrate. In addition, the Monterey Bay Aquarium Research Institute demonstrated that CO_2 clathrates ("solids" in which gas molecules are held in place) tended to be negatively buoyant at depths below 3,000 meters. This property of clathrates would presumably reduce the potential ecological impact of CO_2 on the shallow layers of the ocean, where most marine life occurs. It would also increase the length of time that CO_2 injected would remain in the ocean, thus enhancing the effectiveness of CO_2 sequestration by injection. The goal of this R&D activity is to demonstrate that CO_2 direct injection is safe and environmentally acceptable. See Section 3.3.1 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-331.pdf

- **Iron fertilization**. Fundamental research related to iron fertilization is targeting the magnitude of carbon export down through the water column and the effects on the growth of harmful phytoplankton or diatom species. The goal of this R&D activity is to determine if iron-induced phytoplankton blooms result in the vertical flux (transport) of carbon from the surface waters (export production) to the deep waters. See Section 3.3.2 (CCTP 2005): http://www.climatetechnology.gov/library/2005/tech-options/tor2005-332.pdf

  The Southern Ocean Iron Fertilization Experiment (SOFeX), funded by NSF and DOE, occurred in January-February 2002. These demonstrations aimed to determine the magnitude of export production—that is, how much carbon is transported to the deeper ocean after iron fertilization. The small increase in flux to the deep ocean suggests that iron fertilization would have to be done over a large area of the ocean and sustained for extended periods of time in order to meaningfully reduce the concentration of atmospheric CO_2. NSF has also funded small-scale experiments in the equatorial Pacific Ocean. The mechanics of producing an iron-enriched experimental patch and following it over time was developed in experiments (IronEx I and II) in the equatorial Pacific (Martin et al. 1994; Coale et al. 1996, 1998) and more recently in the Southern Ocean Iron Enrichment Experiment (Boyd et al. 2000).

6.4.4 Future Research Directions

The current portfolio supports the main components of the technology development strategy and addresses the highest priority current investment opportunities in this technology area. For the future, CCTP seeks to consider a full array of promising technology options. From diverse sources, suggestions for future research have come to CCTP's attention. Some of these, and others, are currently being explored and under consideration for the future R&D portfolio. These include:

- **Direct Injection**. The most important R&D need related to direct injection involves improving our understanding of the long-term effects of elevated concentration of CO_2 on marine organisms and ecosystems. This would likely require both *in situ* and laboratory experiments combined with a program of process modeling aimed at a predictive capability for both biological and physico-chemical parameters.

- **Iron Fertilization**. There are a multitude of R&D opportunities regarding the effectiveness and environmental consequences of ocean fertilization. The most pressing question is whether iron enrichment increases the downward transport of carbon from the surface waters to the deep sea. This would help for predicting whether fertilization is an effective carbon sequestration mechanism. Other important questions need to be explored: What are the long-term ecological consequences of iron enrichment on surface water community structure, and on mid-water and benthic processes? How can carbon export best be verified?

The public is invited to comment on the current CCTP portfolio, including future research directions, and identify potential gaps or significant opportunities. No assurance can be provided that any suggested concept would meet the criteria for investment. However, CCTP can be assisted by such comments in its desire to consider a full array of promising technology options.

6.5 Conclusions

The development of the technical, economic, and environmental feasibility and acceptability of CO_2 sequestration strategies has important implications for meeting the needs for food, fiber, and energy while minimizing GHG emissions. As the current energy infrastructure evolves around fossil fuels, the viability of sequestration could provide many options for a future of near-net-zero GHG emissions. Carbon sequestration has the potential to reduce the cost of stabilizing GHG concentrations in the atmosphere, conceivably at lower costs than other alternatives, if successful, and further support domestic and global economic growth.

If carbon sequestration proves technically and economically viable, fossil fuels can continue to play an important role as a primary energy supply. The ability to cost-effectively and safely separate and sequester carbon could have potentially profound implications for the dynamics of food, fiber, and energy production. The current energy infrastructure is designed around fossil fuels, and the viability of carbon capture and sequestration preserves a number of options for an energy future. Although an energy infrastructure later in this century presumably will be different from that of today, without the options that capture and sequestration provide, infrastructure changes must occur sooner and much more dramatically than would otherwise be the case. A more gradual transition that continues the use of fossil fuels, particularly coal, could avoid potentially disruptive consequences that might occur if a rapid change to non-fossil energy sources is required.

6.6 References

Boyd, P.W., A.J. Watson, C.S. Law, E.R. Abraham, T. Trull, R. Murdoch, D.C.E. Bakker, A.R. Bowie, K.O. Buessler, H. Chang, M.A. Charette, P. Croot, K. Downing, R.D. Frew, M. Gall, M. Hadfield, J.A. Hall, M. Harvey, G. Jameson, J. La Roche, M.I. Liddicoat, R. Ling, M. Maldonado, R.M. McKay, S.D. Nodder, S. Pickmere, R. Pridmore, S. Rintoul, K. Safi, P. Sutton, R. Strzepek, K. Tanneberger, S.M. Turner, A. Waite, and J. Zeldis. 2000. A mesoscale phytoplankton bloom in the polar southern ocean stimulated by iron fertilization. *Nature* 407:695-702.

CCTP (See U.S. Climate Change Technology Program)

Coale K.H., K.S. Johnson, S.E. Fitzwater, R.M. Gordon, S. Tanner, F.P. Chavez, L. Ferioli, C. Sakamoto, P. Rogers, F. Millero, P. Steinberg, P. Nightingale, D. Cooper, W.P. Cochran, M.R. Landry, J. Constantinou, R. Rollwagen, A. Trasvina, and R. Kudela. 1996. A massive phytoplankton bloom induced by an ecosystem-scale iron fertilization experiment in the equatorial Pacific Ocean. *Nature* 383:495-501.

Coale, K.H., K.S. Johnson, S.E. Fitzwater, S.P.G. Blain, T.P. Stanton, and T.L. Coley. 1998. IronEx-I, an in situ iron-enrichment experiment: experimental design, implementation and results. *Deep-Sea Research, Part II: Topical Studies in Oceanography* 45:6 919-945.

Davison, J., P. Freund, and A. Smith. 2001. *Putting carbon back into the ground.* Technical Report. Paris: International Energy Agency (IEA) Greenhouse Gas R&D Programme. http://www.ieagreen.org.uk/putcback.pdf

DOE (See U.S. Department of Energy)

Energy Information Administration (EIA). 2004. *International energy outlook 2004.* Washington, D.C: U.S. Department of Energy. http://www.eia.doe.gov/oiaf/ieo/pdf/0484(2004).pdf

Energy Information Administration (EIA). 2005. *Annual energy outlook 2005.* Washington, DC: U.S. Department of Energy. http://www.eia.doe.gov/oiaf/aeo/pdf/0383(2005).pdf

Eve, M.D., M. Sperow, K. Paustian, and R. Follett. 2002. National-scale estimation of changes in soil carbon stocks on agricultural lands. *Environmental Pollution* 116: 431-438.

Follett R.F., J.M. Kimble, and R. Lal. 2001. *The potential of US grazing lands to sequester carbon and mitigate the greenhouse effect*. New York: Lewis Publishers.

Herzog H. 2001. What future for carbon capture and sequestration? *Environmental Science and Technology* 35(7):148A-153A.

Hoffert, et al. 2002. Advanced technology paths to global climate stability: energy for a greenhouse planet. *Science* 298:981-7.

Intergovernmental Panel on Climate Change (IPCC). 2000. *Land use, land-use change, and forestry*. Cambridge, UK: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). 2001a. Chapter 3: the carbon cycle and atmospheric carbon dioxide. In *Climate change 2001: Working Group I: the scientific basis*. Cambridge, UK: Cambridge University Press. http://www.grida.no/climate/ipcc_tar/wg1/095.htm

Intergovernmental Panel on Climate Change (IPCC). 2001b. *Summary for policymakers to climate change 2001: synthesis report of the IPCC third assessment report.* Cambridge, UK: Cambridge University Press. http://www.ipcc.ch/pub/un/syreng/spm.pdf

Intergovernmental Panel on Climate Change (IPCC). 2001c. Chapter 4: technological and economic potential of options to enhance, maintain, and manage biological carbon reservoirs and geo-engineering. In *Climate change 2001: mitigation: contribution of working group iii to the third assessment report.* Cambridge, UK: Cambridge University Press. http://www.grida.no/climate/ipcc_tar/wg3/155.htm

International Energy Agency (IEA) Greenhouse Gas Programme (GHG). 1994a. *Carbon dioxide utilisation.* Cheltenham, UK.

International Energy Agency (IEA) Greenhouse Gas Programme (GHG). 1994b. *Carbon dioxide disposal from power stations.* Cheltenham, UK.

International Energy Agency (IEA) Greenhouse Gas Programme (GHG). 2000. *Barriers to overcome in implementation of* CO_2 *capture and storage*. Report PH3/22. Cheltenham, UK.

Joyce, L.A., and R. Birdsey, eds. 2000. *The impact of climate change on American's forests: a technical document supporting the 2000 USDA Forest Service RPA assessment*, 133. Gen. Tech. Rep. RMRS-GTR-59. Fort Collins, Colorado: U.S. Department of Agriculture. http://www.fs.fed.us/rm/pubs/rmrs_gtr059.pdf

Lal et al. 1998. *The potential of U.S. cropland to sequester carbon and mitigate the greenhouse effect.* Chelsea, MI: Ann Arbor Press.

Martin, J.H., K.H. Coale, K.S. Johnson, S.E. Fitzwater, R.M. Gordon, and 39 others. 1994. Testing the iron hypothesis in ecosystems of the equatorial Pacific Ocean." *Nature* 371.

Perlack, R.D., L.L. Wright, A. Turhollow, R.L. Graham, B. Stokes, and D. Erbach. 2005. *Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply*. ORNL/TM-2005/66. Oak Ridge, TN: Oak Ridge National Laboratory. http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf

Post, W.M., C. Izaurralde, J.D. Jastrow, B.A. McCarl, J.E. Amonette, V.L. Bailey, P.M. Jardine, T.O. West, and J. Zhou. 2004. "Enhancement of carbon sequestration in US soils." *Bioscience* 54:895-908.

Smith, W.H.F., and D.T. Sandwell. 1997. "Global seafloor topography from satellite altimetry and ship depth soundings." *Science* 277:1957-62.

Tuskan, G.A., and M.E. Walsh. 2001. "Short-rotation woody crop systems, atmospheric carbon dioxide and carbon management: a U.S. case study." *The Forestry Chronicle* 77:259-264.

U.S. Climate Change Technology Program (CCTP). 2003. *Technology options for the near and long term*. Washington, DC: U.S. Department of Energy. http://www.climatetechnology.gov/library/2003/tech-options/index.htm Update is at http://www.climatetechnology.gov/library/2005/tech-options/index.htm

U.S. Department of Energy (DOE). 1999. *Carbon sequestration research and development*. DOE/SC/FE-1. Washington, DC: U.S. Department of Energy. http://fossil.energy.gov/programs/sequestration/publications/1999_rdreport/index.html

U.S. Department of Energy (DOE). 2005. *Carbon sequestration technology roadmap and program plan 2005*. Washington, DC: Office of Fossil Energy. http://fossil.energy.gov/programs/sequestration/publications/programplans/2005/sequestration_roadmap_2005.pdf

U.S. Department of Energy (DOE), National Energy Technology Laboratory (NETL). 2004. A sea floor gravity survey of the Sleipner Field to monitor CO_2 migration. *Project Facts.* http://www.netl.doe.gov/publications/factsheets/project/Proj247.pdf

White, C.M., B.R. Strazisar, E.J. Granite, J.S. Hoffman, and H.W. Pennline. 2003. "Separation and capture of CO_2 from large stationary sources and sequestration in geological formations—coalbeds and deep saline aquifers." *Journal of Air & Waste Management* 53:645-715.