Carbon Sequestration

Addressing Global Climate Change

INTRODUCTION

Fossil fuels will remain the mainstay of energy production well into the 21st century. Availability of these fuels to provide clean, affordable energy is essential for the prosperity and security of the United States. However, increased concentrations of carbon dioxide (CO_2) due to carbon emissions are expected unless energy systems reduce the carbon emissions to the atmosphere.

In order to stabilize and ultimately reduce concentrations of this greenhouse gas, it will be necessary to employ carbon sequestration — carbon capture, separation and storage or reuse. Carbon sequestration, along with reduced carbon content of fuels and improved efficiency of energy production and use, must play major roles if the nation is to enjoy the economic and energy security benefits, which fossil fuels brings to the energy mix.

The President's Committee of Advisors on Science and Technology (PCAST) underscored the importance of carbon sequestration in its report "Federal Energy Research and Development for the Challenges of the Twenty First Century." PCAST recommended increasing the U.S. Department of Energy's (DOE's) R&D for carbon sequestration. Specifically, the report stated: " A much larger science-based CO_2 sequestration program should be developed. The aim should be to provide a science-based assessment of the prospects and costs of CO_2 sequestration. This is very high-risk, long-term R&D that will not be undertaken by industry alone without strong incentives or regulations, although industry experience and capabilities will be very useful."

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

To be successful, the techniques and practices to sequester carbon must meet the following requirements: 1) be effective and cost-competitive, 2) provide stable, long term storage, and 3) be environmentally benign. Using present technology, estimates of sequestration costs are in the range of \$100 – \$300/ton of carbon emissions avoided. The goal of the program is to reduce the cost of carbon sequestration to \$10 or less per net ton of carbon emissions avoided by 2015. Achieving this goal would save the U.S. trillions of dollars. Further, achieving a mid-point stabilization scenario (e.g., 550 ppm CO_2) would not require wholesale introduction of zero emission systems in the near term. This would allow time to develop cost effective technology over the next 10-15 years that could be deployed for new capacity and capital stock replacement capacity.

PROGRAM AREAS

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

The program portfolio covers the entire carbon sequestration "life cycle" of capture, separation, transportation, and storage or reuse, as well as research needs for the two other major energy related greenhouse gases of concern, methane (CH_4) and nitrous oxides (N_2O). Specifically, the program has six elements:

- Cost effective CO_2 capture and separation processes.
- CO_2 sequestration in geological formations including oil and gas reservoirs, unmineable coal seams, and deep saline reservoirs.
- Direct injection of CO_2 into the deep ocean and stimulation of phytoplankton growth.
- Improved full life-cycle carbon uptake of terrestrial ecosystems.
- Advanced chemical, biological, and decarbonization concepts.
- Models and assessments of cost, risks, and potential of carbon sequestration technologies.

Benefits

Customer Benefits

- Keeps energy prices low by allowing continued use of low-cost indigenous fossil fuel resources.
- Provides insurance against adverse environmental consequences associated with global climate change.

Supplier Benefits

- Enables U.S. industry to establish a leadership position in a new global market for a novel class of technologies.
- Removes a major concern relative to the continued operation of existing fossil fuel plants.
- Provides flexibility to power producers by enabling the use of indigenous fossil fuels for new generation capacity.
- Expands business opportunities for power producers by adding a commodity to the product slate.

National Benefits

- Results in an estimated cumulative benefit to the U.S. economy of $2.7 trillion through 2050.
- Provides for energy security by enabling use of vast domestic coal resources, which are expected to provide 50 percent of the electricity produced well into the 21st century.
- Allows continued economic growth by stabilizing energy costs.

The Program

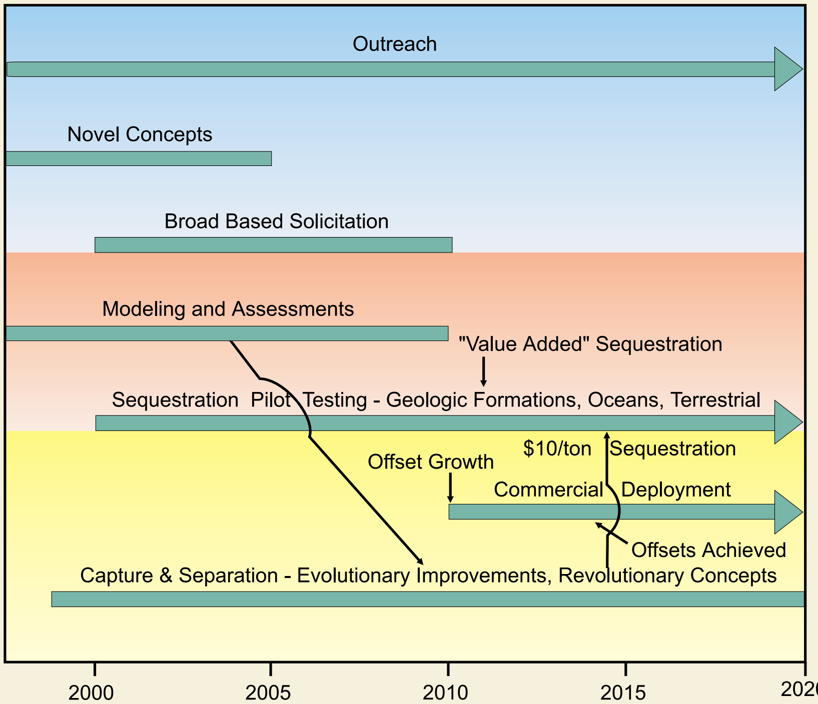
The program goal is to reduce by 2015 the cost of carbon sequestration to $10 or less per net ton of carbon emissions avoided. A program designed to achieve this goal encompasses R&D on a diverse portfolio of sequestration technologies. These technologies offer the best chance of success, both in reducing risks and ultimate cost to the nation, under a carbon constrained future. Since the initiation of the program in 1998, outreach and planning exercises have been conducted to help determine the appropriate direction and focus of the R&D activities. In collaboration with DOE's Office of Science, the report "Carbon Sequestration: State of the Science" identifies the five major areas of R&D needs that serve as the basis for the program. The significant industry participation essential for all phases of the program is achieved through workshops, advisory panels, competitive awards and cost shared partnerships. The near term program will examine and identify a spectrum of science-based sequestration approaches that have the greatest potential to yield the cost-effective technologies that are required. For example, a competitive solicitation was issued in FY1998 and resulted in the selection of 12 innovative novel concepts for the control of atmospheric emissions of CO_2, methane and nitrous oxide. In May 1999 six of the most promising concepts were selected for further study.

Modeling and assessments provide the capabilities to evaluate technology options in a total systems context, considering costs and impacts over the full product cycle. Further, the societal and environmental effects are analyzed to provide a basis for assessing trade-offs between local environmental impacts and global impacts.

In the mid-term, sequestration pilot testing will develop options for direct and indirect sequestration. The direct options involve the capture of CO_2 at the power plant before it enters the atmosphere coupled with "value-added" sequestration, such as using CO_2 in enhanced oil recovery (EOR) operation and in methane production from deep unmineable coal seams. "Indirect" sequestration involves research on means of integrating fossil fuel production and use with terrestrial sequestration and enhanced ocean storage of carbon.

In the long term, the technology products will be more revolutionary and rely less on site-specific or application-specific factors to ensure economic viability.

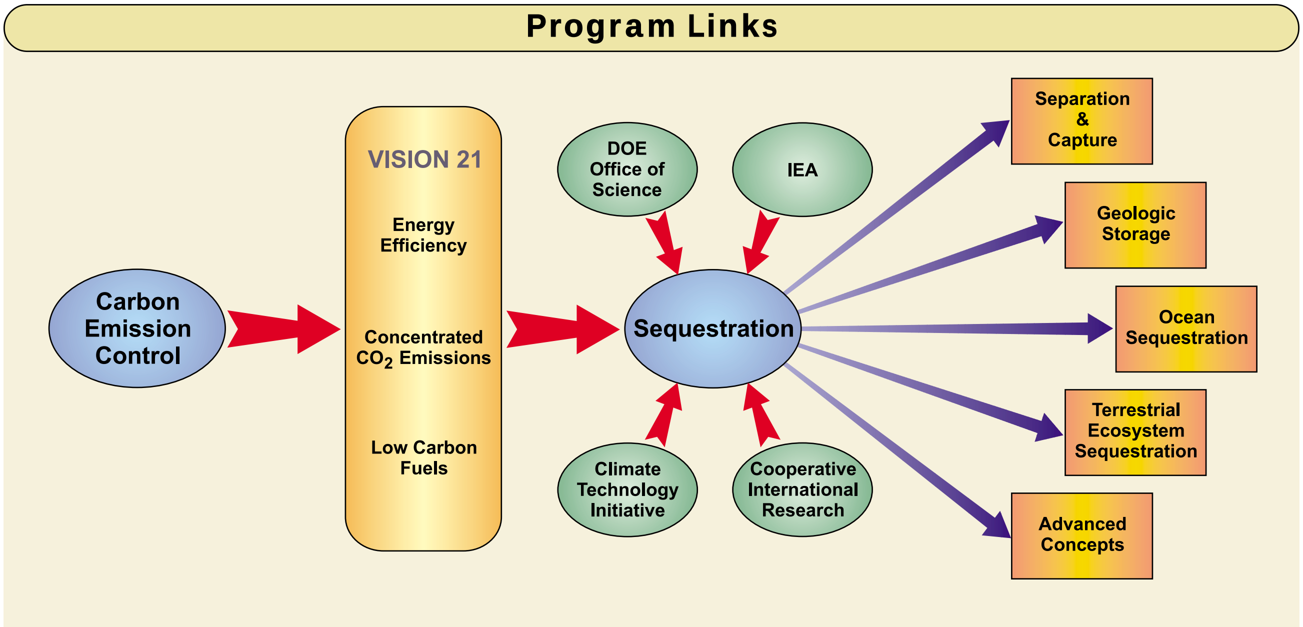
Roadmap



Link To Vision 21 and Other Programs

The CO_2 Sequestration Program is one of three carbon emission control options being addressed under the Coal and Power System Program. The other two options: 1) improving the efficiency of energy use and 2) reduction of the carbon content of fuels are being addressed under the Central Power Systems, Distributed Generation and the Fuel Programs. Under the Vision 21 strategic concept, the systems and modules produce a relatively pure stream of CO_2 that is amenable to capture and sequestration. The development of advanced CO_2 separation technologies under the sequestration program will produce systems that are compatible with the process conditions envisioned for the Vision 21 advanced energy systems. Further, "value added" techniques such as the EOR technologies and coal bed methane extraction are being pursued under Fossil Energy's Oil and Gas RD&D programs.

Moreover, the program supports collaborative efforts with other DOE organizations such as the Office of Science. Continual collaborative activities and workshops are essential to keep all stakeholder groups — industry, end-user, non-profit organizations, academia, national laboratories, the environmental community, and governments — appraised of new developments and to maintain dialogue on the merits of carbon sequestration. International collaboration also is key to developing technology options for mitigating global emissions of greenhouse gases. Program interactions include work with international research groups such as the International Energy Agency (IEA) Greenhouse Gas R&D Programme, and the Climate Technology Initiative (CTI) of the Framework Convention on Climate Change (FCCC). Significant cost sharing and technology transfer to the U.S. are possible through international agreements. These agreements include: cooperative research among the U.S., Japan, and Norway on deep ocean storage of CO_2; and the U.S. and Canadian project on CO_2 sequestration in deep, unmineable coal seams accompanied by coal bed methane production.



DRIVERS

- Availability of clean affordable energy is essential for the prosperity and security of the U.S. and the World in the 21st century.
- Fossil fuel's share of the domestic energy market will increase from 85 percent in 1995 to 90 percent in 2020 reflecting the abundance of the energy resource and the economic and environmental limits on nuclear and renewable alternatives.
- Emissions of CO_2 into the atmosphere is inherent to the use of fossil energy resources for electricity generation, transportation, industrial heat and power and building systems.
- Increased concentrations of CO_2 in the atmosphere due to carbon emissions are expected unless energy systems reduce the carbon load.
- Carbon sequestration — carbon capture, separation, and storage or reuse — must be effective and cost competitive, provide stable, long-term storage and be environmentally benign.
- While much uncertainty is associated with the relationship between CO_2 emissions from energy systems and other human activity and climate change, it is possible that deep cuts in CO_2 emissions will be required over the next 50 to 100 years.

GOALS

- 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.
- Achieve the long-term cost goal of approximately $10/ton of avoided net costs for carbon sequestration.
- Offset at least one-half of the required reduction in global greenhouse gases, measured as the difference in a business-as-usual baseline and a strategy to stabilize concentration at 550 ppm CO_2, beginning in 2025.

Strategies

- Pursue evolutionary improvements in existing CO_2 capture systems and explore revolutionary new capture and sequestration concepts with a view toward significant cost reductions.
- Conduct fundamental studies and field tests to measure the degree to which CO_2 stays sequestered in geologic formations, including oil and gas reservoirs, coal beds and saline formations, and assess the long-term ecological impacts.
- Develop a better understanding of the ecological impacts of ocean fertilization and deep ocean direct injection of CO_2.
- Pursue integrated measures for improving the full life-cycle carbon uptake of terrestrial ecosystems, including farmland and forests, with fossil fuel production and use.
- Develop novel and advanced concepts using chemical, biological, and other approaches to capture, store, and reuse CO_2 from energy production and utilization systems.
- Develop assessment capabilities and analytical tools to assist in the selection of the most promising R&D efforts that have high potential, but significant uncertainties associated with their cost and effectiveness.
- Continue collaboration activities and workshops to keep all stakeholder groups — industry, end-users, non-profit organizations, academia, national laboratories, the environmental community and governments — appraised of new developments and maintain an open dialogue on the merits of carbon sequestration.

Measures of Success

- Reduce the cost of carbon sequestration from \$100 - \$300/ton today to \$10 per net ton of carbon emission avoided by 2015.
- 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 by 2010.
- Establish the viability of larger capacity sequestration approaches suitable for deployment by industry in the post 2015 timeframe.

PROGRAM AREAS

CARBON SEQUESTRATION TARGETS

Offsets in growth of greenhouse gases:
— Technologies by 2015
— 1/2 required reduction by 2015

Cost: $10/ton avoided cost

Based on the report "Carbon Sequestration: State of the Science", the R&D activities are structured around five basic pathways to long-term carbon sequestration.

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

These five pathways are supported by the modeling and assessments program activity.

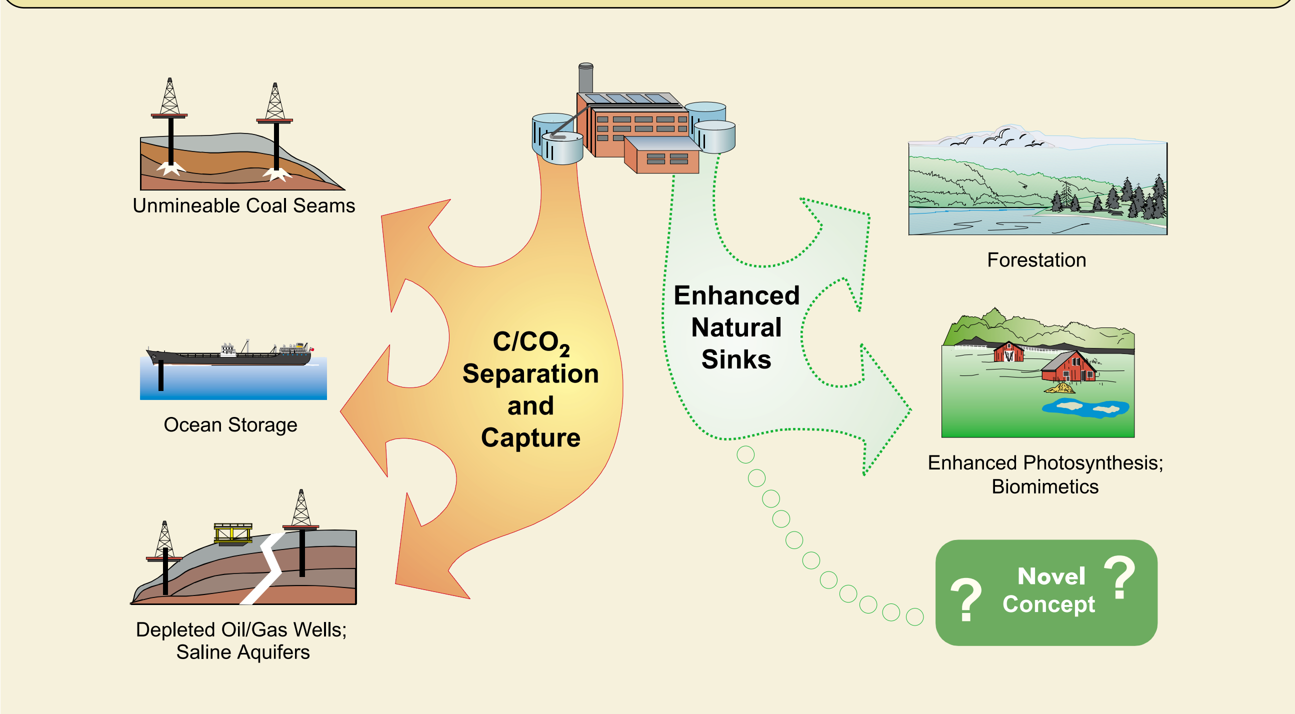
SEPARATION AND CAPTURE

Before CO_2 gas can be sequestered from point sources, it must be captured as a relatively pure gas. CO_2 is routinely separated and captured as a by-product from industrial processes such as synthetic ammonia production, H_2 production, and limestone calcination. However, existing capture technologies are not cost-effective when considered in the context of CO_2 sequestration. Carbon dioxide capture is generally estimated to represent three-fourths of the total cost of a carbon capture, storage, transport, and sequestration system. The program area will pursue evolutionary improvements in existing CO_2 capture systems and also explore revolutionary new capture and sequestration concepts. The most likely options currently identifiable for CO_2 separation and capture include the following:

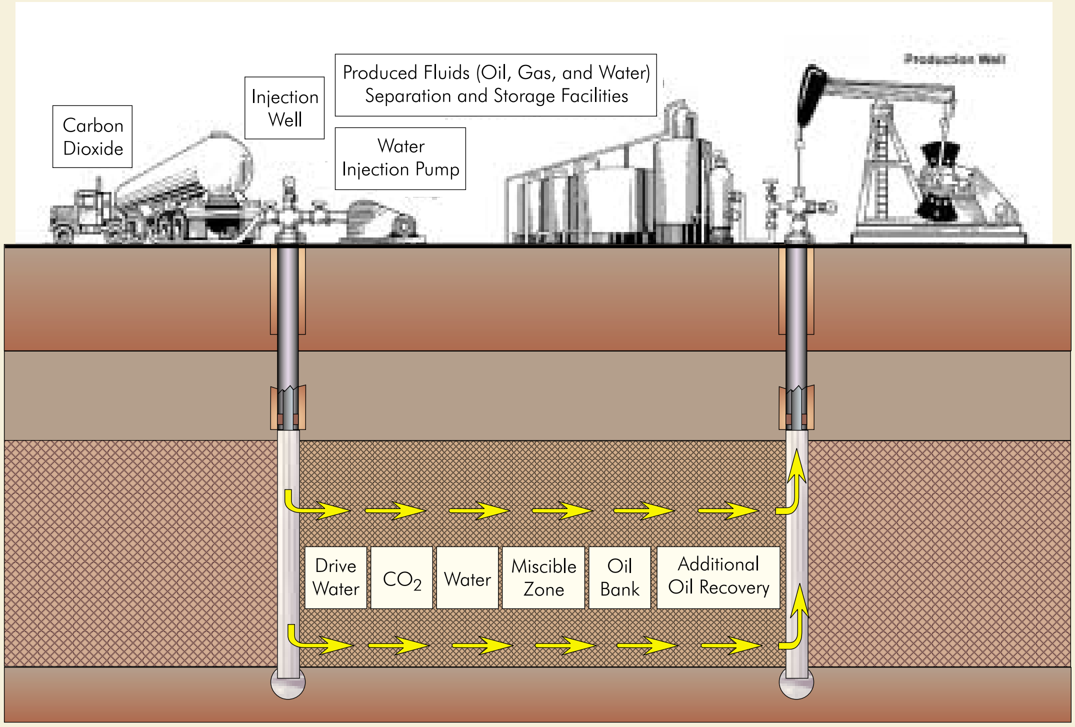
- Absorption (chemical and physical)
- Adsorption (physical and chemical)
- Low-temperature distillation
- Gas separation membranes
- Mineralization and biomineralization

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

Sequestration Sinks



EOR Application



SEQUESTRATION OF CO_2 IN GEOLOGIC FORMATIONS

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

Oil and Gas Reservoirs

In some cases, production from an oil or natural gas reservoir can be enhanced by pumping CO_2 gas into the reservoir to push out the product, which is called enhanced oil recovery (EOR). The United States is the world leader in EOR technology, using about 32 million tons of CO_2 per year for this purpose. From the perspective of the sequestration program, EOR represents an opportunity to sequester carbon at low net cost, due to the revenues from recovered oil/gas. In an EOR application, the integrity of the CO_2 that remains in the reservoir is well-understood and very high, as long as the original pressure of the reservoir is not exceeded. The scope of this EOR application is currently economically limited to point sources of CO_2 emissions that are near an oil or natural gas reservoir.

Coal Bed Methane

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

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

Saline Formations

Sequestration of CO_2 in deep saline formations does not produce value-added by-products, but it has other advantages. First, the estimated carbon storage capacity of saline formations in the United States is large, making them a viable long-term solution. It has been estimated that deep saline formations in the United States could potentially store up to 500 billion tonnes of CO_2 . Second, most existing large CO_2 point sources are within easy access to a saline formation injection point, and therefore sequestration in saline formations is compatible with a strategy of transforming large portions of the existing U.S. energy and industrial assets to near-zero carbon emissions via low-cost carbon sequestration retrofits.

Assuring the environmental acceptability and safety of CO_2 storage in saline formations is a key component of this program element. Determining that CO_2 will not escape from formations and either migrate up to the earth's surface or contaminate drinking water supplies is a key aspect of sequestration research. Although much work is needed to better understand and characterize sequestration of CO_2 in deep saline formations, a significant baseline of information and experience exists. For example, as part of EOR operations, the oil industry routinely injects brines from the recovered oil into saline reservoirs, and the U.S. Environmental Protection Agency (EPA) has permitted some hazardous waste disposal sites that inject liquid wastes into deep saline formations.

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

Ocean Sequestration

CO_2 is soluble in ocean water, and through natural processes the oceans both absorb and emit huge amounts of CO_2 into the atmosphere.

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

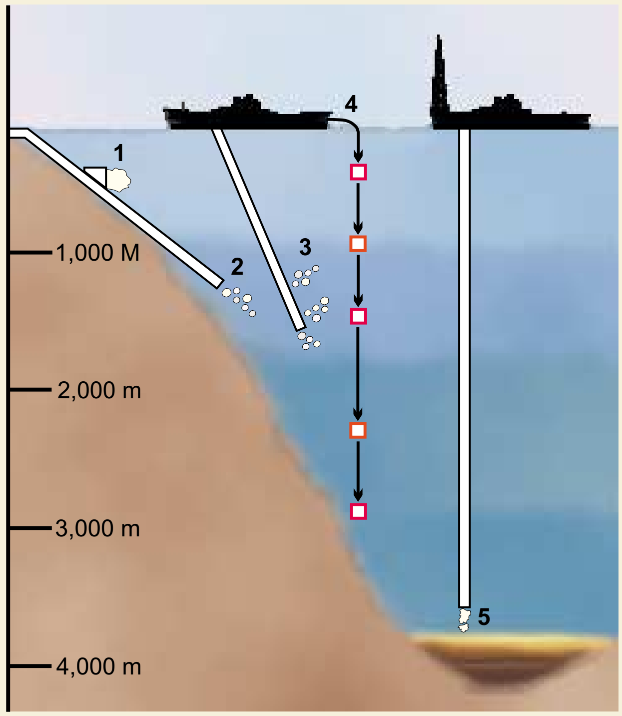
One approach to enhancing the rate of CO_2 absorption in the ocean involves adding combinations of micronutrients and macronutrients to those ocean surface waters deficient in such nutrients. The objective is to stimulate the growth of phytoplankton, which are expected to consume greater amounts of carbon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

Technology exists for the direct injection of CO_2 into deep areas of the ocean; however, the knowledge is not adequate to optimize the costs, determine the effectiveness of the sequestration, and understand the resulting changes in the biogeochemical cycles of the ocean. To assure environmental acceptability, developing a better understanding of the ecological impacts of both ocean fertilization and direct injection of CO_2 into the deep ocean is a primary focus of this program element. It is known that small changes in biogeochemical cycles may have large consequences, many of which are secondary and difficult to predict. Of particular concern is the effect of CO_2 on the pH of ocean water.

Carbon Sequestration in Terrestrial Ecosystems (soils and vegetation)

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

Ocean Disposal of CO_2



Dissolution
1 — Dense Plume
2 — Droplet Plume

Dispersion
3 — Towed Pipe
4 — Dry Ice

Isolation
5 — CO_2 Lake

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

Advanced Concepts (Chemical, Biological, and Other Approaches)

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

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

Concerning biological systems, incremental enhancements to the carbon uptake of photosynthetic systems could have a significant positive effect. Also, harnessing naturally occurring, non-photosynthetic microbiological processes capable of converting CO_2 into useful forms, such as methane and acetate, could represent a technology breakthrough. An important advantage of biological systems is that they do not require pure CO_2 and do not incur costs for separation, capture, and compression of CO_2 gas. This program area will seek to develop novel and advanced concepts for capture, reuse, and storage of CO_2 from energy production and utilization systems based on, but not limited to:

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

Modeling and Assessments

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

EMERGING CONCEPTS

In May 1999, DOE selected six promising concepts for further study from a group of 12 projects competitively selected the previous year. Drawn from 62 proposals, the 12 projects subsequently underwent preliminary feasibility studies.

The six selected projects were extended for 22 months with additional federal funding, permitting larger scale experimentation and more extensive technical and economic assessments. At the end of this second phase, DOE plans to select projects for a final 30-month phase designed to prove engineering feasibility, which will include a pilot- and large-scale testing program.

The six projects chosen by DOE to enter a second phase of development are:

- **Battelle Memorial Institute, Columbus, Ohio**, to evaluate geologic and geochemical processes that could be used to sequester carbon dioxide into deep aquifers that have no known use;
- **Institute for Environmental Management Inc., Palo Alto, California**, working with the California Energy Commission and Yolo County, California, to demonstrate a way to capture methane, a very potent greenhouse gas, from landfills;
- **McDermott Technologies Inc., Alliance, Ohio**, to examine the potential for large-scale carbon dioxide transportation and deep-ocean sequestration;
- **Research Triangle Institute, Research Triangle Park, North Carolina**, to develop an inorganic, palladium-based membrane that would separate hydrogen and concentrated carbon dioxide from hydrocarbon fuels;
- **TDA Research Inc., Wheat Ridge, Colorado**, to study a novel carbon dioxide separation system for a power plant that uses iron- and copper-based sorbents;
- **University of Texas at Austin, Austin, Texas**, to identify optimal saline water-bearing formations in the U.S. for carbon dioxide disposal.

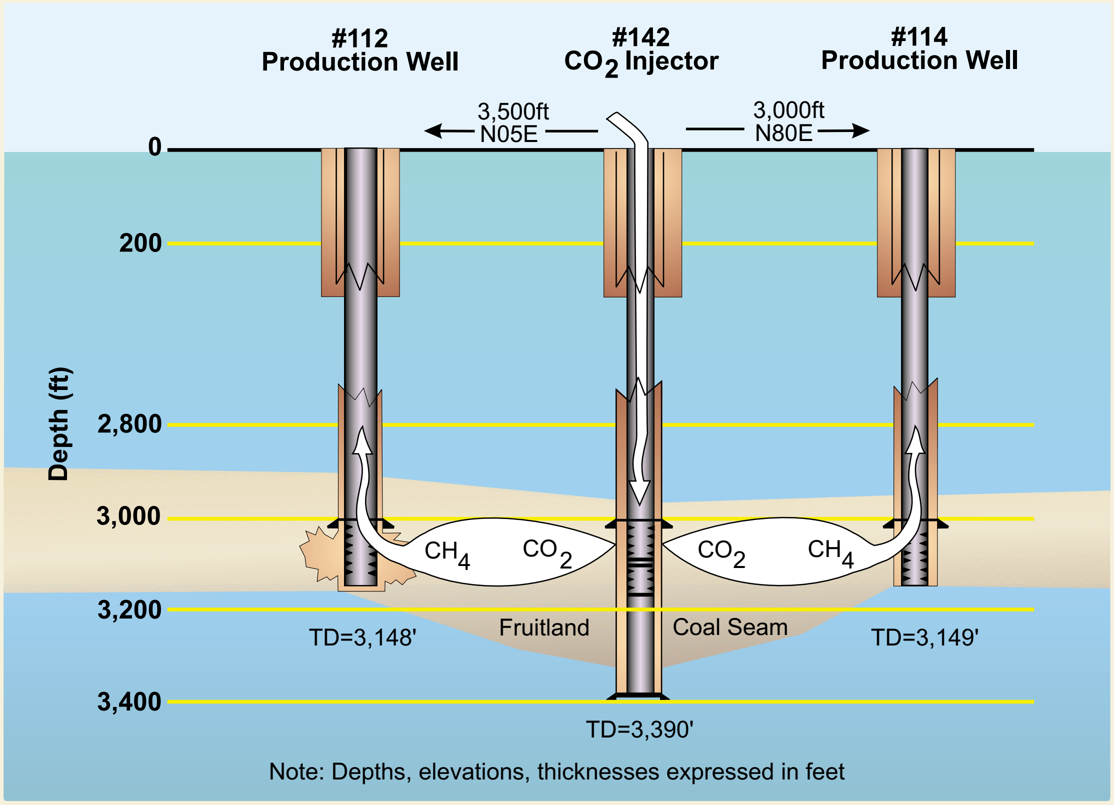
Program Success

Coal Seam Formations

In the United States, estimated coal resources to a depth of 6,000 feet total nearly six trillion tons. Some 90 percent of this amount is considered economically unminable with current technology as either too thin, too deep, or unsafe. These unavailable coal deposits represent a widely dispersed potential option for CO_2 storage, with many of the coals potentially producing methane for commercial use.

For the past 25 years, DOE and its predecessor agencies have been facilitating the evolving recognition and development of coalbed methane resources and technologies. The concept of using injected CO_2 to enhance coalbed methane production is already being field-tested by industry. Much of the data gathered from these tests is proprietary; however, unpublished information supports the retention of the CO_2 in coalbeds. Since 1996, Burlington Resources, a major producer of coalbed methane, has conducted a commercial pilot test for CO_2 injection to enhance coalbed methane recovery. As a spin-off, the pilot sequesters CO_2 as part of its routine operation. Burlington's pilot is located within the northern San Juan basin, in New Mexico, which is the most successful coalbed methane development in the world.

Burlington's Allison Unit



Source: Advanced Resources International

A depiction of a Vision 21 plant and its components as integrated into an existing urban context (namely Roosevelt Island in New York City). Within this plant construct, emissions of carbon dioxide would be dramatically reduced because of higher plant efficiencies. The plant design would also include the option for capturing and sequestering carbon dioxide. Thus, the plant could produce zero emissions — essentially decoupling the use of carbon-based fuels from the production of greenhouse gases.