Carbon Sequestration Technologies

9. Carbon Sequestration and Management

9.1 AUGMENTED OCEAN FERTILIZATION TO PROMOTE ADDITIONAL CO_2 SEQUESTRATION

Technology Description

CO_2 can be continually sequestered in the ocean in a variety of ways, one of the most important of which is the deposit on the ocean floor of the carbon-containing skeletal remains of plankton and diatoms. When carbon is thus removed from solution, it is replaced ultimately by CO_2 drawn from the atmosphere. Yet the vast majority of ocean area is photosynthetically barren, with littoral areas and parts of the Southern Ocean being the most productive. In these photosynthetically barren areas, usually only one nutrient is missing, commonly iron or nitrogen; the supply of this nutrient causes planktonic growth, and with this growth, the basic building blocks of the food chain are present, enabling carbon deposition on the ocean floor and CO_2 drawdown.

The proposal would be to conduct experiments in enriching nutrient-poor sections of the ocean with either iron or nitrogen as a first step to understanding more about the potential to sequester CO_2 safely on the ocean floor through stimulation of growth of phytoplankton.

System Concepts/Representative Technologies

- Iron enrichment experiments have delivered iron sulfate in liquid form from vessels.
- For nitrogen enrichment, proposals have been made to use piped ammonia to provide nitrogen to nitrogen-poor ocean areas.

Technology Status/Applications

- Detailed experiments on iron fertilization have been conducted and reported in the scientific press. No such work has been done to date for nitrogen fertilization, but a pilot experiment to sequester 2 million tons of CO_2 annually has been proposed. Significant R&D will be required.

Current Research, Development, and Demonstration

RD&D Goals

- Develop a clear understanding of technical issues:
  - What is the ultimate removal rate of the detritus of phytoplankton and their grazers to the ocean floor for different amounts of fertilization?
  - To what extent will increased phytoplankton lead to increases in the amount of larger fauna (e.g., fish), and if this leads to a greater harvest, to what extent can/should this be accounted for in atmospheric CO_2 reduction?
- Adequate first order cost estimates per ton of CO_2 sequestered must be developed: one side of the equation would be the amount of CO_2 ultimately removed from the atmosphere per unit of fertilizer. Energy used in making and delivering the fertilizer must be taken into account in this calculation.
- Experimentation will be required to determine the proper depth at which to supply nitrogen. Too shallow a depth will cause loss of some fertilizer to the atmosphere; too great a depth will make the fertilizer unavailable to phytoplankton.

RD&D Challenges

- Understanding the entire cycle of growth and decay that will be stimulated by fertilization. Environmental effects will be crucial: there is concern that too much fertilization could cause some ocean layers to become anoxic as long as the experiment continues, if too much fertilization occurs in a given area.
- The ultimate goal is to find a fertilization rate that is both cost effective (and perhaps beneficial in producing more biomass) and without significant adverse environmental impact.

RD&D Activities

- To date, FE has not undertaken any experiments directly.
- The International Energy Agency (IEA), partly supported by DOE-FE, has begun a program to research the effects of both types of fertilization.
- Some research on ocean fertilization is also being done by the MARICULT program, a European collaborative on marine cultivation.

Commercialization and Deployment

- An international treaty will be needed to precede deployment.

Potential Benefits and Costs

Carbon Reductions

- Theoretical potential is very large; work needs to be done to define maximum rates of fertilization that will have no significant adverse effects. Iron fertilization, which for practical purposes must occur in the Southern Ocean, has a maximum theoretical sequestration effect of 1–2 Gt C/year, but a realistic maximum of far less.

RD&D Expenditures

- FE has not yet proposed funding for RD&D for either type of fertilization. The IEA, partly supported by FE, has begun a program to research the effects of both types of fertilization. Some research on ocean fertilization is also being done by the MARICULT program.
- It is suggested that research on this technology be part of a newly established carbon sequestration program. It is estimated that an annual federal budget on the order of $125M through 2010, $150M through 2020, and $200M through 2030 is needed for this program.

Nonenergy Benefits and Costs

- Potential for significant increase in fisheries and other marine flora and fauna (see above).

Risk Factors

Technical Risk

1 2 3 4 5 ⑥ 7 8 9 10
Low High

- Probably the largest technical risk is that of anoxia, oxygen depletion of certain levels of the ocean. Thus a primary goal of research would be to find out locations and levels of fertilization that would carry no risk of this potential effect.
- To understand costs per ton of CO_2 sequestered, we must know the efficiency per unit of fertilizer. If it takes four times as much nitrogen or iron as thought to sequester one unit of CO_2, the cost per unit will be about four times as high: this kind of calculation is needed to separate economical projects from uneconomical ones.
- Nitrogen will have to be supplied at the proper depth(s), and some experimentation will be required to find these depth(s). Too deep, and it will be unavailable to phytoplankton; too shallow, and some will be lost to the atmosphere.

Commercial Risk

1 2 3 4 ⑤ 6 7 8 9 10
Low High

- Marine environmental protection will probably require significant impact assessment.

Ecological Risk

1 2 3 4 5 6 ⑦ 8 9 10
Low High

- Risks associated with possible oxygen depletion affecting ecology

Human Health Risk

1 ② 3 4 5 6 7 8 9 10
Low High

- Largest risks probably associated with ammonia manufacture and transport for nitrogen fertilization, and with ocean travel, especially in the Southern Ocean.

Economic Risk

1 2 3 4 5 6 7 8 9 10
Low High

- Not applicable. Main risks are probably those associated with public relations (e.g., the perception that humanity would be manipulating the oceans to deal with a problem of its own making).

Regulatory Risk

1 2 3 4 5 6 ⑦ 8 9 10
Low High

- May require international regulatory agreements

Key Federal Actions

- Work together with IEA and other federal agencies currently sponsoring such work to determine proper role for added work to be done by DOE/OFE.
- In conjunction with above, do preliminary work to understand more about how efficiently nitrogen fertilization would work before undertaking a large-scale pilot project that would likely cost at least $50 M.
- In conjunction with bullet No. 1, do preliminary work to track how iron sulfate would disperse in Southern Ocean before starting larger-scale, longer-term project that would look at multi-year effects, with fertilization levels high enough to produce significant sequestration, but below levels that models would predict might begin to cause anoxia.

Generally, before determining added key federal actions, it would be important to interface with other actors to maximize coordination.

9.2 ADVANCED CHEMICAL AND BIOLOGICAL CONVERSION AND SEQUESTRATION

Technology Description

Advanced chemical and biological sequestration and processing is aimed at permanent stable sequestration and recycling of carbon into new fuels and chemical feedstocks. Emissions are reduced through converting CO_2 into an environmentally benign product to reduce atmospheric CO_2 while generating liquid fuels, generating hydrogen as a fuel from coal without CO_2 emissions, and converting CO_2 into organic compounds. The major advantage of these technologies is that they eliminate hazards to humans and the environment that are intrinsic in the disposal of gaseous CO_2. Carbonate disposal does so by forming environmentally benign and thermodynamically stable waste forms; the other approaches instead generate viable products.

System Concepts

- The technology comprises four major areas: chemical sequestration as mineral carbonate, direct solar reduction of CO_2, conversion of coal to H_2 and methanol, and microalagae sequestration. Chemical sequestration takes advantage of the reaction of CO_2 with most magnesium- and calcium-bearing minerals to form solid carbonates. Direct solar reduction of CO_2 is aimed at producing liquid fuels from atmospheric CO_2 by using solar energy to break the CO_2 bond, allowing incorporation of the CO produced into standard fuel synthesis processes. The conversion of coal to H_2 and methanol is accomplished by mineralizing CO_2 during its reaction with steam to produce H_2 and reducing the captured CO_2 to methanol by direct solar reduction. Microalagae sequestration involves passing CO_2 through bubbling stacks, resulting in incorporation of CO_2 to organic carbon.

Representative Technologies

- Chemical sequestration as mineral carbonate
- Direct solar conversion of CO_2 to methanol
- Advanced conversion of coal to H_2
- Microalagae sequestration

Technology Status/Applications

- Chemical sequestration as mineral carbonate: Simple cost estimates for this technology (compared with existing industrial and mining processes) suggest that \$15/ton of CO_2 or \$55/ton of carbon **for conversion and disposal** is a reasonable cost goal to set. For comparison, at a coal-fired electric power plant with 45% conversion efficiency, complete CO_2 disposal at this cost would add \$0.011 to the cost of a kilowatt hour–electric. Further research is required; however, with a reasonable level of support, commercial implementation of the process could start before 2010.
- Direct solar conversion: The process has very promising economics since it produces a useful product. It is estimated that each square meter of mirror involved in the process would produce 3 GJ of fixed energy (44.4 gal of methanol) per year. At this level, methanol production from atmospheric CO_2 could be amenable to very rapid growth through mass production and subsequent operation by small businesses. Between now and 2010, this process will reverse very little CO_2; by 2020, it might fix one megaton of carbon per year. In its mature state, about 50 megatons to one gigaton of carbon might be fixed per year.
- Advanced conversion of coal to H_2: This process is promising because its products are high in value. For each ton of coal consumed, it avoids the emission of ½ ton of carbon and produces instead 440 gal of methanol while using 94 MBtu of solar energy at a cost of \$1.25/MBtu.
- Microalagae sequestration: This technology presents a possible low-cost option for sequestration. So far, it has resulted in a maximum carbon fixation of 100g/m3/day with 96% conversion efficiency of CO_2 to organic carbon. The cost is estimated at \$20/ton of CO_2 (\$73/ton of carbon).

Current Research, Development, and Demonstration

RD&D Goals

- Chemical sequestration as mineral carbonate: The basic principles have been demonstrated. Raw materials exist in vast quantities, and the thermodynamics have been worked out and are favorable, starting from common minerals. The chemistry has been demonstrated but still needs to be optimized. The total cost of R&D for this technology is estimated to be \$3 M/year for 5 years until a pilot plant is built.
- Direct solar conversion: The process is in the research phase. The spectrum of hot CO_2 has only recently been measured. The rates of all of the subsequent reactions are in the literature, but it is necessary to build integral demonstration units to see that all parts of the process play together as expected and to develop a data base for designs. The most basic parts of the R&D have been completed at a cost of \$600K. The chemical kinetics proof of principle will cost another \$800K. The integrated experiment with laser mock-up will cost \$1.5M.
- Advanced conversion of coal to H_2: The concept is in the research stage. It is clear that the CaO has to be developed to allow quicklime to undergo an indefinite number of cycles without caking. Additionally, the reaction of direct solar reduction of CO_2 needs further investigation. The most basic part of the R&D has been completed at a cost of ~600 K. The chemical kinetics proof of principle will cost another \$800K. The integrated experiment with laser mock-up will cost \$1.5M. The solar demonstration at the 10^5 L/year level will cost \$5.5M; the first full 50 million L/year plant module will cost \$100M.
- Microalagae sequestration: The technology is in the developmental stage. Initial tests have been positive and merit further review.

Applications and target markets

- Chemical sequestration as mineral carbonate is applicable to the disposal of CO_2 from such large, concentrated, stationary point sources as electric power plants.
- Direct solar conversion is aimed at producing liquid fuels from effluent or atmospheric CO_2 by using solar energy.
- The H_2 produced during advanced conversion of coal to H_2 could be piped short distances to existing power stations for conversion to electricity either by combustion or fuel cell conversion.
- Microalagae sequestration has applications with ongoing biomass programs and co-firing efforts in utilities.

RD&D Challenges

- Chemical sequestration as mineral carbonate: Research will be required in a broad number of areas from mineral exploration and mining engineering to research in the fairly complex carbonation chemistry of magnesium and calcium silicates. In addition, further development is needed of the chemistry of extracting magnesium from mineral ores and of chemical processes in chemical engineering research.

Current Research, Development, and Demonstration (continued)

RD&D Challenges (continued)

- Direct solar conversion: The spectrum of hot CO_2 has only recently been measured. It is necessary to build integral demonstration units to see that all parts of the process play together as expected and to develop a data base for designs. Basic research is needed in CO_2 and CO, high-temperature materials, ceramics and metals, advanced combustion, and fluid dynamics and modeling.
- Advanced conversion of coal to H_2: Technology needs include research into the basic nature of the reaction between coal, steam, and quicklime; basic properties, including theoretical understanding of CO_2 and CO; and basic research in high-temperature materials, ceramics and metals, advanced combustion, and fluid dynamics and modeling.
- Microalagae sequestration: R&D is needed in genetic engineering to improve plant uptake and in various feedstream properties to determine the robustness of plants.

RD&D Activities

- Programs in mineral fixation, solar-thermal production of methanol, and coal-based production of H_2 and methanol are under way at LANL. A program in microalgae supported by EPRI is active at the University of Miami.

Potential Benefits and Costs

Carbon Reductions

Carbon reductions from this pathway are not likely to occur without policy changes, and such changes are not considered in this study.

- Chemical sequestration as a mineral carbonate: 100% efficacy at $15/ton for CO_2. (@60% power plant (IGCC) efficiency—395 MtC/year at 300 GW)
- Direct solar reduction of CO_2: 60% efficacy assuming recycling at $7/ton for CO_2 with credits for methanol. (@60% power plant (IGCC) efficiency—236 MtC/year at 300 GW)
- Advanced conversion of coal to H_2: [60 to 80]% efficacy at $7/ton for CO_2. (@60% power plant (IGCC) efficiency—270 MtC/year at 300 GW—70% efficacy of process)
- Microalagae sequestration: 100% efficacy at $20/ton for CO_2
- (@60% power plant (IGCC) efficiency—395 MtC/year at 300 GW)

RD&D Expenditures

- It is suggested that research on this technology be part of a newly established carbon sequestration program. It is estimated that an annual federal budget on the order of $125M through 2010, $150M through 2020, and $200M through 2030 is needed for this program.

Market

- The versatility of the technologies could allow them to capture a large fraction of the CO_2 mitigation market if CO_2 credits were implemented.

Nonenergy Benefits and Costs

- These technologies are largely environmentally benign and result in no hazardous byproducts. They also produce commercially viable products that may be used by industry. Finally, the versatility of these technologies will crosscut several major areas of concern relating to CO_2 management.

Risk Factors

Technical Risk

1 2 3 4 ⑤ ⑥ 7 8 9 10

Low High

- These technologies are novel approaches.

Commercial Risk

1 2 3 4 ⑤ 6 7 8 9 10

Low High

- The technologies are still too young to fully evaluate the commercial risk.

Ecological Risk

1 ② 3 4 5 6 7 8 9 10

Low High

- No hazardous byproducts are associated with these technologies.

Human Health Risk

1 ② 3 4 5 6 7 8 9 10

Low High

- The risks involved are limited to the individual processes themselves.

Economic Risk

1 2 3 4 ⑤ 6 7 8 9 10

Low High

- These technologies are still too young to fully evaluate the economic risk.

Regulatory Risk

1 2 ③ ④ 5 6 7 8 9 10

Low High

- The regulatory processes are driven at a large scale and by mining; however, this is true of any large-scale comprehensive method.

Key Federal Actions

- Government/industry partnerships are recommended.
- The establishment of a long-term sequestration R&D program is recommended.

9.3 TERRESTRIAL STORAGE OF CO_2

Technology Description

Terrestrial storage of CO_2 involves capturing CO_2 and injecting it into subsurface repositories such as deep coalbeds, depleted oil and gas reservoirs, and deep, confined saline aquifers. The technology for subsurface injection is readily adaptable from the petroleum industry for application to CO_2 sequestering. These technologies include the drilling and completion of injection wells, compression and long-distance transport of gases, subsurface reservoir characterization, multi-component reservoir simulation, and experience with the operational issues of CO_2 injection for enhanced oil recovery. Terrestrial storage in geologic repositories will reduce GHG emissions by long-term sequestration from the atmosphere. The injection of CO_2 into depleted oil and gas reservoirs and deep coalbeds has the potential for storing CO_2 and yielding commercially valuable hydrocarbons.

System Concepts

- CO_2 is captured, processed, compressed, and transported by pipeline to a geologic structure having sufficient reservoir porosity and permeability for commercial utility.
- Storage may entail geochemical reactions that tend to form carbonates in silicic host rock, enhancing containment.

Representative Technologies

- Technologies will borrow extensively from the petroleum industry in areas of drilling, stimulation, and completion of injection wells; processing, compression, and pipeline transport of gases; operational experience of CO_2 injection for enhanced oil recovery; subsurface reservoir engineering and characterization including multi-component reservoir simulation; and natural gas storage in saline aquifers.

Technology Status/Applications

- The petroleum technology is readily adaptable to subsurface CO_2 storage.
- Natural gas is routinely transported and stored in subsurface reservoirs and aquifers.
- Reservoir storage and containment parameters have yet to be defined.
- Economic feasibility, capital and operating costs for the construction of a CO_2 collection and transport infrastructure at varying distances from a stationary sources have yet to be determined.

Current Research, Development, and Demonstration

RD&D Goals

- Conduct geologic and reservoir engineering studies to define required storage integrity, flow properties, and volume capacity of geologic repositories.
- Estimate the costs of infrastructure development for terrestrial CO_2 disposal.
- Conduct fate and transport modeling studies, including geochemical reactions with formation fluids and rocks.
- Quantify the safety and environmental requirements of a storage repository.
- Demonstrate the commercial feasibility of the technology with a field test.

RD&D Challenges

- Identify sufficient CO_2 storage capacity in economical proximity to large, stationary sources.
- Establish reservoir criteria for storage integrity, quantify storage capacity, and evaluate environmental acceptability.
- Modify existing reservoir simulation codes to included CO_2/carbonate geochemistry for long-term fate and transport studies.

RD&D Activities

- DOE/FE has initiated a study of the economic, legal, environmental, and social issues use of the Mt. Simon aquifer underlying portions of the U.S. Midwest.
- Commercial recovery of coalbed methane by CO_2 injection has been demonstrated by industry.
- FETC has identified promising sites for CO_2 sequestration in Texas where large power plants are close to high-capacity depleted oil and gas reservoirs.

Recent Success

- Statoil has a project to store 1 million tonnes per year of CO_2 from the Sleipner Vest gas field in a sandstone aquifer 1000 m beneath the North Sea.
- Dakota Gasification Company recently signed a contract to transport 2 million tonnes of CO_2 per year captured from the gasification of lignite to PanCanadian Petroleum for enhanced oil recovery in Canada.
- Industry has demonstrated injection of CO_2 into coalbeds for enhanced methane production.

Commercialization and Deployment

- About 70 oil fields worldwide use CO_2 for enhanced oil recovery.
- No commercial aquifer storage sites for CO_2 are operating in the United States.
- There is commercial and industrial experience with over 400 wells for injecting industrial waste into deep aquifers.
- The Mt. Simon aquifer underlying Illinois, Indiana, Michigan, Kentucky, and Pennsylvania has been approved for industrial waste disposal and underlies a region with numerous fossil energy power plants.
- Injection of CO_2 into depleted oil and gas reservoirs and deep coalbeds can provide incremental hydrocarbon recovery.

Potential Benefits and Costs

Carbon Reductions

- It might be feasible to inject a large fraction of the CO_2 produced from U.S. power plants on site without a long-distance pipeline transportation infrastructure.

RD&D Expenditures

- It is suggested that research on this technology be part of a newly established carbon sequestration program. It is estimated that an annual federal budget on the order of $125M through 2010, $150M through 2020, and $200M through 2030 is needed for this program.

Nonenergy Benefits and Costs

- Injecting CO_2 into oil fields could recover incremental oil, boosting U.S. production and reducing oil imports.
- Successful implementation would create domestic and international market opportunities for U.S. companies for site-specific studies and project implementation.

Expected Cost Per Ton of Carbon Sequestered

- The cost of injecting CO_2 into depleted oil and gas reservoirs is typically less than $10/ton. Costs have been estimated to range from $2 to $8/ton of CO_2 for aquifer storage, excluding power plant modifications. The cost of injecting CO_2 into depleted oil and gas reservoirs is less than $10/ton. Costs have been estimated at $5 to 15/ton of CO_2, equivalent to $18 to $55/ton of carbon. Assuming a 1% per year reduction in total system costs, the cost per ton of carbon can be reduced to $17 to $52 by 2000 and to $16 to $47 by 2010. Assuming an accelerated RD&D program goal of a 3% per year reduction in total system costs, the costs can be reduced to $16 to $47 by 2000 and $11.61 to $34.82 by 2010.

Risk Factors

Technical Risk

1 2 ③ 4 5 6 7 8 9 10

Low High

- The technology for subsurface injection of CO_2 can be readily adapted from the petroleum industry. Site-specific long-term fate and transport studies are required to demonstrate successfully sequestration.

Commercial Risk

1 2 3 4 5 ⑥ 7 8 9 10

Low High

- Individual components of petroleum technology have yet to be integrated and a pilot field test successfully completed for commercial acceptance. The potential domestic and international market for CO_2 sequestration services is very large and intimately related to the use of fossil fuels, the implementation of carbon taxation, and regulatory and governmental activities. A significant infrastructure investment for the collection, transportation, and disposal of CO_2 would be required.

Ecological Risk

1 2 3 ④ 5 6 7 8 9 10

Low High

- Ecological risk is primarily associated with the collection and transportation infrastructure. CO_2 storage in a geologically stable repository presents minimal risk to the biosphere. Land subsidence of uplift over time is a possibility. R&D needed to find out if there is a possible subsurface ecology risk.

Human Health Risk

1 2 ③ 4 5 6 7 8 9 10

Low High

- CO_2 is present in low concentrations in the atmosphere. Human health risk is primarily associated with industrial accidents in the collection and transportation of CO_2.

Economic Risk

1 2 3 4 5 6 7 8 9 10

Low High

- Not applicable. Economic feasibility has yet to be evaluated or demonstrated. A field pilot test with an industrial partner is needed to establish capital and operating costs and operational parameters. The rate of return on capital invested for infrastructure is unknown.

Regulatory Risk

1 2 3 4 ⑤ 6 7 8 9 10

Low High

- Regulatory requirements are likely to be similar to those for the natural gas transportation and storage industries.

Key Federal Actions

- Survey data collected by federal and state agencies and industry on the distribution, formation, and potential storage capacity of depleted oil and gas reservoirs, deep coalbeds, and saline aquifers suitable for CO_2 sequestration.
- Demonstrate technical and economic feasibility and perform environmental assessment to attract commercial interest and support for using captured CO_2 for long-term sequestration.
- Conduct field demonstration projects of CO_2 storage in different types of geologic repositories.

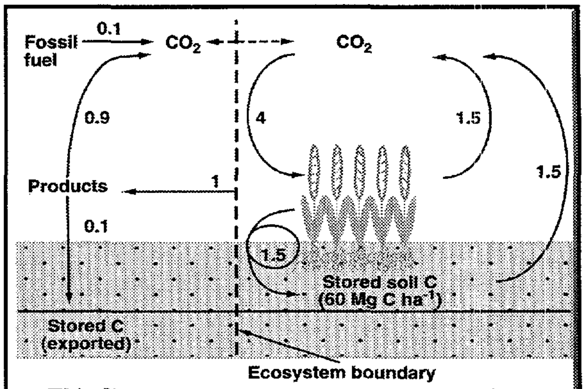
9.4 CARBON SEQUESTRATION IN SOILS

Technology Description

The IPCC (Second Assessment Report, 1995 Chapter 23, Working Group II) estimates that between 400 and 800 Mt C/year could be sequestered in agricultural soils worldwide by implementation of appropriate management practices that also increase agricultural productivity. These practices include increased use of crop residues, reduced tillage and restoration of wasteland soils. Overall, however, the capacity of soils to store carbon is finite and, if best practices are employed worldwide, can lead to a new equilibrium soil organic matter (SOM) content in from 50 to 100 years.

System Concepts

- When grasslands are broken for agricultural use, SOM in the densely rooted upper half-meter or so of soil is exposed to oxidation with consequent emission of CO_2 to the atmosphere.
- When wetlands are drained, their highly organic soils are aerated and exposed to oxidation with consequent CO_2 emissions into the atmosphere. Further, the dry surfaces of drained organic soils are exposed to wind erosion, and the dispersed organic particles are quickly oxidized.
- The net effects on SOM of forest land conversions to agriculture are more difficult to estimate and depend on the mineral composition, aeration, and acidity of the original soils. They depend, too, on climate and on the crop or pasture vegetation that replaces the forest. Even though a net gain in SOM is possible in some cases, maintenance of current forests and reforestation offer much greater opportunity for carbon sequestration.



This diagram represents an agroecosystem (crop field) with the general direction and dimensions of CO_2 fluxes. Arrows allude to photosynthesis, plant and soil respiration, plant litter, and soil organic matter transformations. Carbon sequestering practices lead to an imbalance between carbon gains and losses and therefore to an increase in soil organic matter.

Representative Technologies

- Minimum tillage, now practiced on more than 30% of U.S. farmlands, leads to increases in SOM.
- Increased return of crop residues to the soil provides a source of organic matter, some of which remains in the soil and increases carbon sequestration.
- Irrigation and appropriate use of fertilizers increases crop and root biomass, thereby increasing SOM.
- Return of agricultural lands to forests and grasslands initiates recovery of SOM content, and revegetation of degraded lands stabilizes them against further erosion and increases carbon storage in the soil.
- Plant breeding and genetics to increase belowground storage.

Current Research, Development, and Demonstration

RD&D Goals

- Development of minimum tillage and residue management practices that are both sustainable and profitable and adaptable to all climatic regions.
- Understanding the sensitivity of carbon-sequestration techniques to climatic changes.
- Understanding the environmental, social, and economic consequences of large-scale biomass production on lands currently producing food and feed crops.

RD&D Activities

- In 1995, USDA supported precision agriculture research at 15 locations for a total of $4.4M. By 1996, 125 people were involved in precision agriculture research, and funding was $26M—half for precision agriculture and half for supporting research. About $9M was transferred to land-grant universities through the Cooperative State Research Education and Extension Service.
- Private investment in precision agriculture is growing. A University of Georgia home page on precision farming links lists more than 50 companies in Australia, Canada, France, Germany, Sweden, the United Kingdom, and the United States offering precision agriculture services. Companies involved in precision agriculture research include Case IH, John Deere, Leica, Lockheed Martin, Agrium, Farmland Industries, and Monsanto.

Recent Success

- Aboveground carbon storage is complemented by belowground carbon storage in soil organic matter and roots. Roots of trees, shrubs and herbaceous species can grow considerably deep into the soil profile thereby reducing the possible release of CO_2 into the atmosphere. A 1994 article in *Nature* reported that pasture grasses planted to increase beef production in the South American savannas may remove in a year as much as 2 Gt of CO_2 from the atmosphere. Carbon storage occurred as deep as a meter in the savanna soil.

Commercialization and Deployment

- The need for increased sequestration of carbon in soils will not, of itself, motivate farmers. The practices cited can be fostered with incentives in the form of subsidies keyed to amounts of carbon sequestered. More practical would be demonstrations that these practices increase farm profitability. Minimum tillage has already been shown to do so. In the developed world, improvements in irrigation and fertilization management can be effected through a range of satellite-based, computer-controlled techniques known as "precision farming." More traditional extension methods may be needed, for now, in the developing countries, although with the development of appropriate institutions, high-tech solutions may be deployable there, too.

Potential Benefits and Costs

Carbon Reductions

- The carbon loss from cultivated soils has been estimated at 55 Gt worldwide. The current carbon stock in cultivated soils is 167 Gt to a depth of 1 m. Calculations have been made that 40 GtC can be stored in soil over a 50 to 100 year period (linear rates of 400 to 800 MtC/year).

RD&D Expenditures.

- It is suggested that research on this technology be part of a newly established carbon sequestration program. It is estimated that an annual federal budget on the order of $125M through 2010, $150M through 2020, and $200M through 2030 is needed for this program.

Market

- At present, there is no market value for carbon in soils. Recognition of such a market would encourage land managers to apply techniques leading to carbon storage (e.g., precision farming, minimum tillage, deep rooted crops, agro-forestry, riparian areas).

Nonenergy Benefits and Costs

- Within range, an increase in soil organic matter leads to improvements in soil tilth, reduction of soil erosion, and improvements in crop nutrition.

Risk Factors

Technical Risk

1 2 [✓ 3] 4 5 6 7 8 9 10

Low High

- Obtaining accurate national and regional carbon accounting.

Commercial Risk

1 2 [✓ 3] 4 5 6 7 8 9 10

Low High

- Market value of carbon sequestration activities.

Ecological Risk

1 [✓ 2] 3 4 5 6 7 8 9 10

Low High

- Carbon sequestering activities should lead to ecological enhancement.

Human Health Risk

1 2 [✓ 3] 4 5 6 7 8 9 10

Low High

- Public perception of genetically-altered organisms

Economic Risk

1 2 3 4 [✓ 5] 6 7 8 9 10

Low High

-

Regulatory Risk

1 2 3 4 [✓ 5] 6 7 8 9 10

Low High

- Public opposition to precision farming and gene manipulation.

Key Federal Actions

- Maintain existing research infrastructure (USDA/Forest Service, ARS, NRCS).
- Provide incentives for farmer adoption of carbon sequestration practices and other resource conserving practices.
- Include carbon sequestration as another goal of land use planning/land management.

9.5 ELEMENTAL CARBON SEQUESTRATION

Technology Description

The production of hydrogen by the thermal decomposition of natural gas, followed by sequestration or sale of the particulate carbon formed, is an alternative to the conventional method in which steam reforming of natural gas is followed by a water/gas shift and separation and sequestration of CO_2.

$$CH_4 = C + 2H_2$$

System Concepts

- The production of hydrogen from fossil and carbonaceous fuels, with reduced CO_2 emission to the atmosphere, is key to the production of hydrogen-rich fuels for mitigating the CO_2/GHG climate change problem. The basic reaction is the high-temperature thermal decomposition of natural gas to elemental carbon and gaseous hydrogen.
- The reasons for setting forth this technology as the basis for a CO_2 mitigation process are as follows:
  - It would provide a zero-CO_2-emissions process for producing hydrogen.
  - The process energy required to produce a mole of hydrogen would be lower than for any other production method, including steam reforming of methane.
  - It would be a one-step reaction process with separation of hydrogen from carbon.
  - The resulting carbon solid could be relatively easily separated from the gas stream.
  - The carbon could be more readily disposed of than CO_2. It would be a relatively stable and storable solid that could be landfilled, stored in mines, or sunk to the ocean floor. Carbon sequestration may be more acceptable than CO_2 sequestration.
  - The carbon would be pure and could be marketed as a commodity. Millions of tons of carbon are used yearly as a strengthening agent in rubber tires and as pigments in paints, printing inks, and facsimile machines. It is also possible to use carbon as a soil additive. Another possibility is to use carbon as a construction material in civil works, highways, and housing. Just as ash from coal is a useful product, carbon from methane could be considered the ash of natural gas with respect to the greenhouse problem.
  - The projected cost of production of hydrogen from methane decomposition is competitive with the cost of steam reforming of methane. *If the carbon produced could be sold as a commodity, the net cost of this process would be much lower than the cost of steam reforming* of hydrogen.
  - The hydrogen could be used efficiently in fuel cells or reacted with CO_2 to produce methanol, which would fit well into the current liquid fuel infrastructure.
- The main negative aspect of this technology is that only a little more than half the energy from the natural gas resource would be extracted in the form of hydrogen. However, this ratio is not much worse than for other CO_2 sequestration technologies. Furthermore, the carbon energy, is not destroyed. It may be possible to use it at a later date when atmospheric CO_2 is less problematic.

System Components

- Thermal decomposition reactor
- Carbon separation and utilization

Representative Technologies

- High-temperature reactors
- Molten metal reactors
- Particulate removal from the gas stream

Technology Status/Applications

- Thermal decomposition of methane to produce carbon black has been practiced for years in the thermal black process. Hydrogen has been produced from methane decomposition on a demonstration scale in a catalyzed fluidized bed. The plasma decomposition of methane has been performed on a pilot plant scale. However, these are relatively inefficient processes with efficiencies of only about 50% because they have not been specifically geared to hydrogen production.

Current Research, Development, and Demonstration

RD&D Goals

- To use methane decomposition as a CO_2 mitigation technology, it is necessary to develop an efficient reactor that would produce hydrogen continuously at a thermal efficiency of >70%. Several reactor types have been proposed, including a molten metal reactor. Study is required to investigate the autocatalytic effect of the carbon formed on the kinetics of the methane decomposition reactor as it affects reactor design.
- The possibilities for using large amounts of carbon as a material commodity should be investigated. It could become a new construction material or a soil enhancer for farming. The lifetime stability of terrestrially sequestered carbon needs clarification.

Applications and Target Markets

- This technology is geared toward marketing decarbonized fuels, hydrogen and methanol. The methanol could be produced from the reaction of hydrogen with CO_2 from a coal-fired power plant. The methanol would then be used in either internal combustion or fuel cell vehicles. Thus the carbon would be used twice—once to generate electrical power and a second time to power transportation.
- The carbon would be directed toward material commodity markets—tires, pigments, and construction materials.

RD&D Challenges

- Develop a continuous high-thermal-efficiency thermal decomposition reactor for methane.
- Develop efficient separation systems for separating solid carbon from a gaseous hydrogen stream.
- Determine the applications of solid carbon as a materials commodity and the stability of carbon in a sequestered condition.

RD&D Activities

- A small conceptual research program funded by DOE has been performed at BNL for $50K. Kvaerner Company in Norway has worked on the plasma decomposition of methane but not on the thermal degeneration. The old thermal black process has not been developed further.

Commercialization and Deployment

Potential Benefits and Costs

Carbon Reductions

- Thermal decomposition of natural gas, storing or using the carbon as a material, and using the hydrogen as such or converting it to methanol for use in fuel cells for transportation could reduce carbon emissions by 80% compared with using gasoline derived from petroleum to power vehicles. The cost per ton of CO_2 deleted from the atmosphere would be negligible because of the revenue from selling methanol or hydrogen as a fuel replacing gasoline to drive engines. The mass of carbon to be sequestered or marketed would be on the order of 400 million tons, which is less than 25% of the mass of CO_2 emissions from coal and oil currently consumed in the United States. (See the Systems Concepts section for further discussion of benefits.)

RD&D Expenditures

- It is suggested that research on this technology be part of a newly established carbon sequestration program. It is estimated that an annual federal budget on the order of $125M through 2010, $150M through 2020, and $200M through 2030 is needed for this program.

Market

- This technology is a basic global technology applied to on a prime large fuel resource for removal of carbon (i.e., natural gas). It would produce a prime carbon-free fuel, hydrogen, that could be used as a basic fuel in all engines and conversion devices. It would supply the hydrogen economy without producing and emitting CO_2.

Nonenergy Benefits and Costs

- This technology produces carbon as a materials commodity for construction and the infrastructure. It produces hydrogen to be used for fuel and for chemical and fertilizer production.

Risk Factors

Technical Risk
1 ② ③ 4 5 6 7 8 9 10
Low High

Commercial Risk
1 ② ③ 4 5 6 7 8 9 10
Low High

Ecological Risk
1 ② ③ 4 5 6 7 8 9 10
Low High

Human Health Risk
1 ② ③ 4 5 6 7 8 9 10
Low High

Economic Risk
1 ② ③ 4 5 6 7 8 9 10
Low High

Regulatory Risk
1 2 3 4 ⑤ 6 7 8 9 10
Low High

Key Federal Actions

- A 10-year effort cofunded by government and industry is recommended to reach commercial goals.

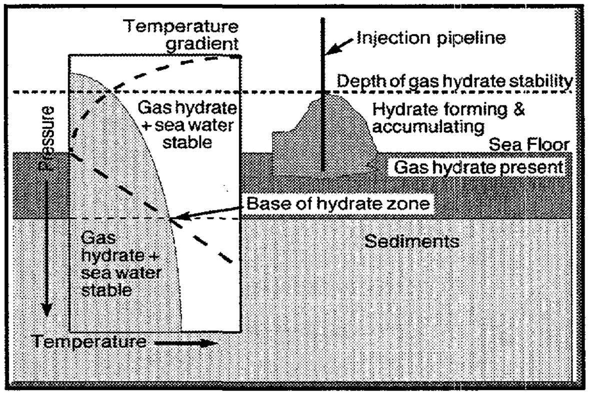
9.6 OCEAN STORAGE

Technology Description

Gas hydrates are nonstoichiometric compounds in which the gas molecules are encaged within a host crystal lattice of water molecules (46 H_2O tetrahedral coordinated water molecules and eight cavities for CO_2 and CH_4) with an ideal composition of $8M46H_2O$ (i.e., n=5.75). The water molecules that do not react chemically with the encaged molecules can form CO_2/CH_4 mixtures. CO_2 could be pumped into regions such as deep oceans where hydrate is stable and sequestered as accumulated gas hydrate. The drawing is a conceptual cross-section of CO_2 introduced to deep seafloor or within seafloor sediments. (The diagram shows stability field of gas hydrate relative to hydrothermal and geothermal pressure and temperature gradients in the ocean and seafloor.)

System Concepts

- In arctic oceans, permafrost regions, and deep oceans, the pressure and temperature conditions favor gas hydrate stability. At deep ocean depths, CO_2 hydrates form below temperatures of 10°C. As a result of these same in situ processes, CH_4 hydrates form on the ocean floor and within ocean sediments. This CH_4 stabilized as hydrate is a major reservoir of GHGs. The sequestration process is the opposite of systems envisioned to extract CH_4 hydrates from the seafloor as an energy source. CO_2 could be piped into regions where hydrate is stable and sequestered as accumulated gas hydrate at the seafloor-ocean interface or within the accumulating sediments (the possible reservoir is basically unlimited because of the areal extent of ocean and permafrost regions where hydrates are stable). The advantages of the gas hydrate sequestration pathway are that hydrate formation results in a significant reduction in volume for equivalent mass and that the process may be less rate dependent than relying on CO_2 mixing with sea water.



Conceptual cross-section of CO_2 introduced to deep seafloor.

Representative Technologies

- Performance assessment
- Deep ocean engineering
- Deep ocean science
- Fate and transport geochemistry
- Three-dimensional characterization and monitoring

Technology Status/Applications

- This is a frontier technology. Japan, India, and the United States are investigating the somewhat reverse process of mining the seafloor or arctic gas hydrate for methane. Since this work is still developmental, costs are difficult to estimate. However, since the ambient pressure and temperature conditions at the seafloor form the gas hydrate, the basic cost is for the deep water pipelines to bring CO_2 as a gas or liquid to the appropriate location where the pressure and temperature conditions favor clathrate stability. Research suggests that ocean sequestration of CO_2 would cost from \$5 to \$50 per tonne of carbon depending on the site and other factors.

Current Research, Development, and Demonstration

RD&D Goals

- Understanding of CO_2 fate and transport in deep ocean waters and sediments.
- Comparative cost and risk evaluation among this and other technology pathways.

RD&D Challenges

- Performance assessment: engineering risk/decision analysis, total system environmental risks, and comparative cost and risk evaluation among this and other technology pathways.
- Deep ocean engineering: completion to targeted areas, size to handle volumes, durability, and cost-effectiveness.
- Deep ocean science: characterization of pressures and temperatures, deep ocean currents and transport, deep ocean sedimentation, and deep ocean ecosystems.
- Fate and transport geochemistry: geochemistry complex mineral and fluid interaction with CO_2-bearing phases, fate of clathrates at various temperature and depths (pressures) in the ocean, and modeling of temporal (over 100 years) and spatial behavior.
- Three-dimensional characterization and monitoring: volumes and suitability, location, areal extent, flow and availability, geostatistics.

Current Research, Development, and Demonstration (continued)

RD&D Activities

- RD&D activities for CO_2 sequestration as gas hydrates are not currently funded. Ongoing basic science programs, waste storage programs, and engineering development programs for fossil energy extraction may provide an existing foundation for the development of the gas hydrate sequestration pathway. Some of the basic science (e.g., deep ocean science, fate and transport geochemistry) can be leveraged by ongoing general R&D in these fields. In the broad sense, the level of activity for general research in these related fields is as follows:
  - deep ocean science sponsored by NSF ($20M), NRL ($100M), IPOD ($5M), industry ($10M), and foreign agencies ($10M).
  - fate and transport (e.g., geochemistry and three-dimensional characterization and monitoring) sponsored by NSF ($1M), NRL ($1M), other government agencies (e.g., USGS) ($1M), and foreign agencies ($50M).
- The general components of the RD&D activities for deep ocean engineering and performance assessment technologies are being developed for fossil energy extraction and waste storage. The current levels of RD&D for fossil energy extraction and waste storage are as follows:
  - deep ocean engineering sponsored by NRL ($50M), IPOD ($5M), industry ($10M), and foreign agencies ($150M).
  - performance assessment sponsored by DOE ($100M), NRC ($10M), EPA ($10M), industry ($100M), and foreign agencies ($100M).

Recent Success

Commercialization and Deployment

Potential Benefits and Costs

Carbon Reductions

- 100% efficacy (assuming no significant leakage during transport and total conversion to clathrate and mixing with deep waters) at $0.20 to $10/tonne of CO_2 ($0.73 to $37/tonne of carbon).

RD&D Expenditures

- It is suggested that research on this technology be part of a newly established carbon sequestration program. It is estimated that an annual federal budget on the order of $125M through 2010, $150M through 2020, and $200M through 2030 is needed for this program.

Market

- The large potential reservoir, the reliance on natural processes (e.g., the enhanced stability field due to the deep ocean or permafrost region pressure and temperature conditions), and the areal distribution of deep oceans and arctic region represented in the gas hydrate sequestration pathway would allow this pathway to capture a large fraction of the CO_2 mitigation market if CO_2 credits are implemented.

Nonenergy Benefits and Costs

- These technologies are largely environmentally benign and may facilitate the production of ocean methane clathrates as an energy source. For example, the formation of CO_2 clathrates may reduce the subsidence related to methane extraction.

Risk Factors

Technical Risk

1 2 3 4 5 6 ⑦ 8 9 10

Low High

- These technologies are novel approaches.

Commercial Risk

1 2 4 5 6 7 8 9 10

Low High

- The technologies are still too young to fully evaluate the commercial risk.

Ecological Risk

1 2 3 4 ⑤ 6 7 8 9 10

Low High

- No hazardous byproducts are associated with these technologies. However, the effects on methane release need to be evaluated through a total system performance assessment.

Human Health Risk

1 2 ③ 4 5 6 7 8 9 10

Low High

- The risks involved with these technologies are limited to the individual processes themselves.

Economic Risk

1 2 3 4 5 6 7 8 9 10

Low High

- These technologies are still too young to fully evaluate the economic risk.

Regulatory Risk

1 2 3 4 ⑤ 6 7 8 9 10

Low High

- The regulatory processes are driven at a large scale and by mining; however, this is true of any large-scale comprehensive method.

Key Federal Actions

- The establishment of a long-term sequestration R&D program and government/industry partnerships.