CO_2 Capture, Reuse, and Sequestration Technologies for Mitigating Global Climate Change

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Introduction

Fossil fuels currently supply over 85% of the world's energy needs. They will remain in abundant supply well into the 21st century. They have been a major contributor to the high standard of living enjoyed by the industrialized world. We have learned how to extract energy from fossil fuels in environmentally friendly ways, controlling the emissions of NO_x, SO_2, unburned hydrocarbons, and particulates. Even with these added pollution controls, the cost of fossil energy generated power keeps falling.

Despite this good news about fossil energy, its future is clouded because of the environmental and economic threat posed by possible climate change, commonly referred to as the "greenhouse effect". The major greenhouse gas is carbon dioxide (CO_2) and the major source of anthropogenic CO_2 is combustion of fossil fuels.

The potential impacts of global climate change are many and varied, though there is much uncertainty as to the timing and magnitude (Watson *et al.*, 1996). Because of the potential adverse impacts, the world community has adopted the Framework Convention on Climate Change (see Box 1). The urgency of their work was recently underscored when the Intergovernmental Panel on Climate Change (IPCC) issued their *Second Assessment Report* which stated that "the balance of evidence suggests a discernible human influence on global climate". The goal of stabilization of greenhouse gas emissions at their 1990 levels in the year 2000 will not be met by the vast majority of countries. Based on this experience, it is obvious that more aggressive technology responses are required if we want to control greenhouse gas emissions.

Below are some reasons why research into CO_2 capture, use, and disposal technologies should be considered as part of our technological response to climate change concerns:

- It is a prudent measure since there are only a limited number of strategies to reduce greenhouse gas emissions. The field of CO_2 capture and sequestration is still in its infancy, with many questions needing to be addressed to make these technologies viable. At this time, it is judicious to explore all potential mitigation options in a balanced way, so that a broad range of strategies are available to help meet future policy goals.

- These technologies provide a long-term greenhouse gas mitigation option that allows for continued large-scale use of our abundant fossil energy resources.

- With continued research, these technologies have the potential to provide a cost-effective mitigation option in response to policies aimed at limiting greenhouse gas emissions and ultimately stabilizing greenhouse gas concentrations in the atmosphere.

- These technologies can be used as an alternate option in case new non-fossil energy sources like solar or present non-fossil energy sources like nuclear cannot gain sufficient market share and/or acceptance.

- These technologies could be a low cost mitigation option if hydrogen were to become a major energy carrier.

Objective

In 1991, the US DOE (Fossil Energy and Energy Research) contracted with the MIT Energy Laboratory to identify, assess, and prioritize research needs for the capture and non-atmospheric sequestration of a significant portion of the CO_2 emitted from fossil fuel-fired electric power plants. The final report (Herzog *et al.*, 1993) for that project was issued in July, 1993. However, much new knowledge has been gained since that time. The objective of the current project is to review the new research results generated since 1993, reassess the priority research needs, and to then revisit the conclusions of the 1993 assessment (see Box 2).

Technology Descriptions

Avoidance of CO_2 emissions through physical capture of CO_2 from fossil fuel power plants was first proposed by Marchetti (1977), with sequestration of the captured CO_2 in the deep ocean. In the US, preliminary studies were conducted at Brookhaven National Laboratory (Albanese and Steinberg, 1980; Steinberg, 1984). However, it was not until almost 1990 that significant research efforts were undertaken in this field. Since then, many studies have been carried out and a number of conferences have been held on options for the capture and sequestration or reuse of CO_2 from large stationary sources.

Today the two key challenges that must be addressed by the international research community investigating CO_2 removal technologies are reducing costs and finding suitable methods of sequestration. While there is much work to do, results to date give reasons for optimism. This section reviews the current status of capture, sequestration, and utilization technologies.

Box 1. International Activities on Climate Change

December 21, 1990	The Intergovernmental Negotiating Committee (INC) created by the United Nations. Negotiations begin on a climate treaty.
June, 1992	The Framework Convention on Climate Change (FCCC) adopted by 143 countries in Rio at the “Earth Summit”. Among its provisions is a goal to stabilize greenhouse gases at their 1990 levels by the year 2000.
March 21, 1994	The FCCC comes into force 90 days after its ratification by 50 countries, including the United States.
March, 1995	The first Conference of the Parties (COP-1) to the FCCC held in Berlin. The Climate Technology Initiative (CTI) is adopted. One of its provisions is to “assess the feasibility of developing longer-term technologies to capture, remove or dispose of greenhouse gases and strengthen relevant basic and applied research.”
February, 1996	CTI Task Force 7 formed to accelerate international collaboration for R&D in the field of medium- and long-term technologies relating to greenhouse gas capture and disposal.
June 5, 1996	The Intergovernmental Panel on Climate Change (IPCC) *Second Assessment Report* states that “the balance of evidence suggests a discernible human influence on global climate”.
July, 1996	COP-2 held in Switzerland. US Under Secretary of State Timothy Wirth states that the US will press for an “agreement that sets out a realistic, verifiable, and binding medium-term emissions target.”
November, 1996	In Australia, President Clinton calls “upon the community of nations to agree to legally binding commitments to fight climate change. We must stand together against the threat of global warming. A greenhouse may be a good place to raise plants; it is no place to nurture our children.” (*Washington Post*, Nov. 23, 1996)
December, 1997	COP-3 scheduled to be held in Japan. On the agenda: emissions targets and timetables.

Box 2. Conclusions of the 1993 DOE/MIT Research Needs Assessment

1. To implement CO_2 capture and sequestration on a national scale will decrease power plant net efficiencies and significantly increase the cost of electricity. To make responsible societal decisions, accurate and consistent economic and environmental analysis of all alternatives for atmospheric CO_2 mitigation are required.

2. Commercial CO_2 capture technology, though expensive and energy intensive, exists today.

3. The most promising approach to more economical CO_2 capture is to develop power plant systems that facilitate efficient CO_2 capture.

4. While CO_2 disposal in depleted oil and gas reservoirs is feasible today, the ability to dispose of large quantities of CO_2 is highly uncertain because of both technical and institutional issues. Disposal into the deep ocean or confined aquifers offers the potential for large quantity disposal, but there are technical, safety, liability, and environmental issues to resolve. Therefore, the highest priority research should focus on establishing the feasibility of large scale disposal options.

5. Land or ocean disposal will require research to better understand environmental impacts. Even with such information, the public may be reluctant to accept some disposal options.

6. While transportation of compressed, liquid CO_2 has been demonstrated, important issues involving cost, safety, liability, and institutional barriers to large scale deployment remain.

7. Individual options for using captured power plant CO_2 in an alternate fuel, as an industrial feedstock, or as an agricultural growth enhancer are not promising for sequestration of significant amounts of CO_2.

Capture Technologies

The idea of capturing CO_2 from the flue gas of power plants did not start with concern about the greenhouse effect. Rather, it gained attention as a possible economic source of CO_2, especially for use in enhanced oil recovery (EOR) operations where CO_2 is injected into oil reservoirs to increase the mobility of the oil and, therefore, the productivity of the reservoir. Several commercial CO_2 capture plants were constructed in the late 1970s and early 1980s in the US (Arnold *et al.*, 1982; Hopson, 1985; Kaplan, 1982; Pauley *et al.*, 1984). The North American Chemical Plant in Trona, CA, which uses this process to produce CO_2 for carbonation of brine, started operation in 1978 and is still operating today. However, when the price of oil dropped in the mid-1980s, the recovered CO_2 was too expensive for EOR operations and all of the other CO_2 capture plants were closed. Several more CO_2 capture plants were subsequently built (Barchas and Davis, 1992; Sander and Mariz, 1992) to take advantage of some of the economic incentives in the Public Utility Regulatory Policies Act (PURPA) of 1978 for “qualifying facilities”.

Historically, CO_2 capture processes have required significant amounts of energy, which reduces the power plant’s net power output. For example, the output of a 500 MW_e (net) coal-fired power plant may be reduced to 400 MW_e (net) after CO_2 capture. This imposes an “energy penalty” of 20% (i.e., (500-400)/500). The energy penalty has a major effect on the overall costs. Table 1 shows typical energy penalties associated with CO_2 capture -- both as the technology exists today and how it is expected to evolve in the next 10-20 years.

TABLE 1. Typical Energy Penalties due to CO_2 Capture

Power Plant Type	**Today**	**Future**
Conventional Coal	27 - 37% (Herzog and Drake, 1993)	15% (Mimura *et al.*, 1997)
Gas	15 - 24% (Herzog and Drake, 1993)	10 - 11% (Mimura *et al.*, 1997)
Advanced Coal	13 - 17% (Herzog and Drake, 1993)	9% (Herzog and Drake, 1993)

In addition to power plants, there are a number of large CO_2-emitting industrial sources that could also be considered for application of capture and sequestration technologies. In natural gas operations, CO_2 is generated as a by-product. In general, gas fields contain up to 20% (by volume) CO_2, most of which must be removed to produce pipeline quality gas. Therefore, sequestration of CO_2 from natural gas operations is a logical first step in applying CO_2 capture technology. In the future, similar opportunities for CO_2 sequestration may exist in the production of hydrogen-rich fuels (e.g., hydrogen or methanol) from carbon-rich feedstocks (e.g., natural gas, coal, or biomass). Specifically, such fuels could be used in low-temperature fuel cells for transport or for combined heat and power. Relatively pure CO_2 would result as a byproduct (Williams, 1996; Kaarstad and Audus, 1997).

Geological Sequestration Technologies

Underground sequestration in geological formations is a major option for disposing of CO_2. The main options for underground sequestration are (Herzog *et al.*, 1993):

- Sequestration in active oil reservoirs
- Sequestration in coal beds
- Sequestration in depleted oil and gas reservoirs

- Sequestration in deep aquifers
- Sequestration in mined salt domes or rock caverns

The main issues are uncertainties in the volumes available for sequestration (see Box 3), the long-term integrity of the sequestration, and the costs associated with CO_2 transport to the sequestration site and the sequestration operation itself (Herzog *et al*., 1993; Freund and Ormerod, 1997). Sequestration integrity is important not only to prevent the unintended return of CO_2 to the atmosphere, but also for concerns about public safety and the potential liability should there be a catastrophic release. CO_2 gas is heavier than air and, if a large release were to occur, it could displace air at the surface and cause asphyxiation. The relative merits of these options are described in Table 2 and include issues of sequestration capacity, cost, sequestration integrity and feasibility.

TABLE 2. Comparison of Geological Sequestration Options

Sequestration Option	**Relative Capacity**	**Relative Cost**	**Sequestration Integrity**	**Technical Feasibility**
Active oil wells (EOR)	Small	Very Low	Good	High
Coal beds	Unknown	Low	Unknown	Unknown
Depleted oil/gas wells	Moderate	Low	Good	High
Deep aquifers	Large	Unknown	Unknown	Unknown
Mined caverns/ salt domes	Large	Very High	Good	High

Geological sequestration is currently being demonstrated -- in September 1996, Statoil of Norway began storing CO_2 from the Sleipner West gas field into a sandstone aquifer 1000 m beneath the North Sea. The CO_2 is injected from a floating rig through five pipes at a rate of 20,000 tonnes/week (corresponding to the rate of CO_2 produced from a 140 MW_e coal fired power plant). Earlier pilot studies showed that most of the CO_2 will react to form solid calcite, with some dissolving in the groundwater and some remaining as a separate phase. While Statoil has not disclosed information on the project costs, they have stated that the cost is less than the Norwegian carbon tax of \$50 per tonne CO_2. An international research effort is being organized to monitor and document this effort so the experience can be built on by future endeavors.

Exxon and Pertamina have recently announced plans to inject CO_2 from their natural gas field at Natuna into a deep aquifer 1000 m below the South China Sea floor, 375 miles east of Singapore (*Boston Globe*, p. 33, Nov. 20, 1995). Natural gas from the reservoir, one of the world's largest, will be liquefied to produce LNG for sale to the Far East, but it contains over 70% CO_2 by volume which must first be separated and sequestered. Averaged over a 30 year period, the 150 trillion cubic feet (about 4 trillion cubic meters) of stored carbon dioxide corresponds to the volume emitted through continuous production of 38,000 MW_e of electricity from coal fired power plants.

Box 3. Worldwide Sequestration Potential for CO_2

The IEA Greenhouse Gas R&D Programme estimated the worldwide sequestration potential in billion tonnes of CO_2 (Ormerod, 1994). As reflected in the large ranges below, this task is very difficult given all the uncertainties:

Deep Ocean	5,100 - >100,000
Deep Aquifers	320 - 10,000
Depleted Gas Reservoirs	500 - 1100
Depleted Oil Reservoirs	150 - 700

Since the world produces about 22 billion tonnes of CO_2 annually from energy production, it is clear that the theoretical capacities are more than adequate. Research is required to help narrow these ranges and determine what portion of this potential can be practically exploited.

Ocean Sequestration Technologies

The ocean represents the largest potential sink for anthropogenic CO_2 (see Box 3) and it already contains the estimated equivalent of 140,000 billion tonnes of CO_2 (compared with annual worldwide anthropogenic emissions of about 22 billion tonnes of CO_2). Furthermore, discharging CO_2 directly to the ocean would accelerate the ongoing, but slow, natural processes by which over 90% of present-day emissions are currently entering the ocean *indirectly* (Sarmiento, 1993). As indicated schematically by Figure 1, discharging CO_2 directly to the ocean would reduce both peak atmospheric CO_2 concentrations and their rate of increase. However, CO_2 concentrations in the atmosphere and ocean will equilibrate over time scales of 1000 years or more, regardless of where the CO_2 is discharged. The ocean sequestration concept was first mentioned by Marchetti (1977) who conceived of piping CO_2 into the outflow of the Mediterranean Sea, where it would sink deeper into the Atlantic. Some follow-up work was undertaken in the late 1970s (e.g., Hoffert *et al*., 1979; Baes *et al*., 1980), but most research has taken place in the past six years, principally by researchers in Japan, Norway and the United States.

Ocean sequestration strategies can be evaluated according to sequestration efficiency (avoidance of CO_2 leakage back to the atmosphere), cost and technical feasibility, and environmental impact.

Considering these issues, a consensus is developing that the best ocean sequestration strategies, at least initially, are the discharge of CO_2 as a liquid at a depth of 1000 m or greater, either from a bottom mounted pipe or through a pipe towed from a moving ship.

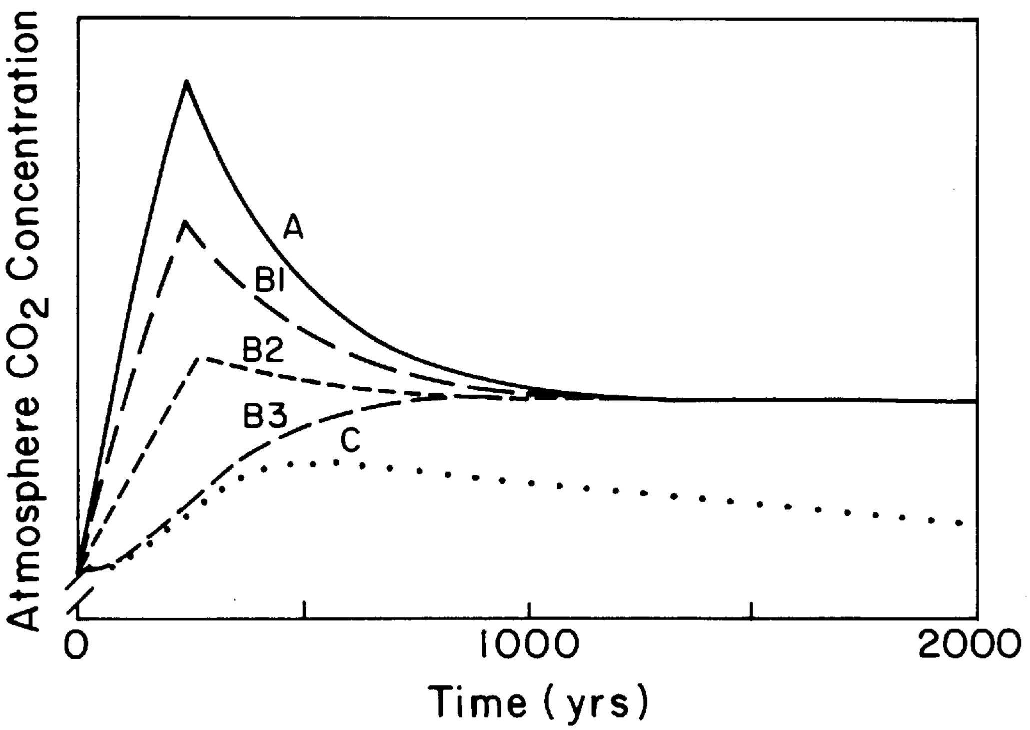

Figure 1. Qualitative illustration of the effect of ocean sequestration on atmospheric CO_2 concentrations, based on a constant CO_2 emission rate for 250 years and then no further emissions. Line A represents business-as-usual emissions to the atmosphere. Because the atmosphere and ocean are out of equilibrium, atmospheric concentrations will decrease after emissions stop until an equilibrium is achieved at around 1000 years. Lines B1, B2, B3 show the effect of ocean sequestration with either increasing quantity of CO_2 injected to the ocean or increasing depth of sequestration, leading to longer residence times. Line C shows the potential effect of carbonate chemistry (or solid deposition on the ocean floor) whereby some of the CO_2 becomes permanently sequestered, never to return to the atmosphere. (after Wilson, 1992.)

Direct Utilization Technologies

Recycling or reuse of CO_2 emitted or captured from power plants would seem to be an attractive alternative to the sequestration options discussed in the two preceding chapters. However, the problem is finding enough uses to sequester a significant amount of the CO_2 generated. Today, the total industrial use of CO_2 in the US is about 40 million tonnes per year -- only about 2% of the 1.7 billion tonnes produced annually from our power plants. About 80% of this use is in enhanced oil recovery (EOR) and is supplied from CO_2 gas wells at prices much cheaper than power plant CO_2. Therefore, the challenge is to find new and larger uses that will consume the CO_2 or otherwise sequester it from the atmosphere. The candidate uses fall into three main categories: industrial uses, chemical conversion to fuels, and biological conversion to fuels.

Industrial uses. To illustrate the mismatch in quantities between power plant emissions and industrial use potential for CO_2, assume that CO_2 was substituted for fossil fuel feedstocks in all US plastics production. This total transformation of the US plastics industry to CO_2 feedstocks would require less than 100 million tonnes of CO_2 per year, about 5% of the 1.7 billion tonnes produced annually from US power plants. There are a number of other fairly small-scale industrial applications that could use captured CO_2 (Aresta and Tommasi, 1997). In a vigorous CO_2 mitigation effort, many small industrial activities could be converted to power plant CO_2 feedstreams, but the potential total impact would be much less than 1% of the total power plant CO_2 generated.

Carbonate minerals. Another possibility is to use CO_2 to make stable solid products like carbonate minerals that can be returned to the environment. This concept really could be considered as another form of geological sequestration. Weathering of alkaline rocks (especially calcium and magnesium silicates) is a natural method of CO_2 sequestration (Kojima *et al.*, 1997). To enhance the rate of the natural process, the authors suggest that olivine sand and wollastonite could be pulverized, dissolved, and reacted with power plant CO_2 to form magnesium and calcium carbonates. Energy needs for the pulverization generate CO_2 that is from 1 to 15% of the CO_2 sequestered. While the process seems feasible, large amounts of rock must be transported and handled -- several times the weight of the CO_2 sequestered -- as well as significant amounts of makeup hydrochloric acid. Lackner and Butt (1997) have done some preliminary calculations on this concept that suggest its potential for significant CO_2 mitigation at costs of about $30 per tonne of CO_2 sequestered (not including costs of capture) and they note that the scale of the operations would be somewhat smaller than the present scale of coal mining activities in the US. While further research is needed to support these preliminary estimates, this is an interesting possibility.

Chemical conversion to fuels. A large use that could begin to match power plant emissions of CO_2 is to “recycle” the CO_2 back to a fossil fuel that could reduce the use of virgin fossil fuels. Unfortunately, reducing CO_2 back to carbon requires at least 80% of the energy that is generated from burning a typical coal, and when processing losses are considered, there may be no net gain or even a loss of energy. Unless this energy comes from non-fossil sources, additional CO_2 is generated. And if non-fossil energy is available, in most cases it would be better used to substitute for the burning of coal in the first place.

Biological conversion to fuels. Benemann (1997) has reviewed the possibilities in a recent paper that analyzes the different options and suggests fruitful areas for further research. Microalgae are of particular interest because of their rapid growth rates (up to ten times that of trees) and potential for significantly higher efficiency solar conversion than land plants. These microscopic plants would be grown in large open ponds, into which power plant flue gas or pure CO_2 (captured from power plants) is introduced as small bubbles. The estimated mitigation costs for this type of scheme would be up to $100 per tonne CO_2 recycled (with significant opportunities for further cost reduction); a pond area of about 50 - 100 square kilometers would be needed for a 500 MW_e power plant (Benemann and Oswald, 1996). After harvesting, the biomass would be converted to a fossil fuel replacement, preferably a high value liquid fuel such as biodiesel. Microalgae systems require a combination of land, water, and climate resources seldom found in conjunction with power plants. These factors currently constrain the likely reductions by microalgae systems in the US to a few tens of millions of tonnes of CO_2 per year -- perhaps 1% of present fossil CO_2 emissions. Again, this could be one element of a diverse set of utilization options that contribute to mitigation.

Results

This section gives some preliminary results of our work to date.

Capture Technologies. The key challenge regarding CO_2 capture technology is to reduce the overall cost by lowering both the energy and the capital cost requirements. While costs and energy requirements for today's capture processes are high, opportunities for significant reductions exist since researchers have only recently started to address these needs. The following approaches appear the most fruitful:

- Implement the easy opportunities first, such as those in the natural gas industry and industries like ammonia and ethylene.

- Improve today's commercially available chemical absorption processes. Key research needs are to develop more energy efficient solvents and reduce equipment size and cost.

- Use oxygen instead of air for combustion, producing a flue gas from which CO_2 is easily captured. Research needs include reducing oxygen costs, addressing the problems associated with retrofitting existing plants, and optimizing the efficiency of new plants.

- Integrate CO_2 capture into advanced power plants, such as IGCC or fuel cells. Research needs to address improved separation techniques (e.g., membranes), improved shift catalysts, and heat and power integration.

Geological Sequestration Technologies. Several steps need to be implemented to further the development of land-based CO_2 sequestration. It should be emphasized that some of the needed information is actually available, but not accessible due to proprietary and anti-trust considerations; these obstacles must be overcome in order to avoid costly duplication. The needs include:

- Perform a quantitative assessment of sequestration volume at depleted gas and oil field sites in the US. The study should be national in scope and include input from the American Petroleum Institute, the American Gas Association and the National Petroleum Council.
- Assess the storage integrity characteristics of depleted fields and their suitability for re-opening to inject CO_2. Also, determine how best to "finish" currently producing wells for future CO_2 sequestration.
- Establish a methodology for assessing the long-term integrity and ecological impacts of sequestration, as well as the safety risk for underground reservoir types.
- Test modifications in EOR operations to maximize CO_2 sequestration as well as oil recovery.
- Continue testing the use of CO_2 to increase coal bed methane production and explore synergies whereby coal bed methane, produced with the enhancement of waste CO_2, could fuel power plants resulting in no net CO_2 emissions.
- Finally, because deep aquifer sequestration holds the best long-term promise, but is also the least certain, this option deserves special consideration:
  - Conduct basic theoretical and laboratory research concerning the fluid, thermal and geological properties of deep aquifers in order to refine technical feasibility criteria.
  - Conduct a comprehensive survey of industrial and government data on the location and nature of deep aquifers throughout the US (including off-shore aquifers) that meet the feasibility criteria. Much of the needed data does not exist and will need to be collected.
  - Conduct an economic analysis of capital and operating costs for this option with specific attention to identified sites in the US.
  - Conduct a domestic field demonstration project.

Ocean Sequestration Technologies. The key research needs in the area of ocean sequestration are:

- Physical-chemical interactions between CO_2 and seawater, including the likelihood of hydrate formation on surfaces of CO_2 droplets contained in droplet plumes, and the interaction between CO_2-enriched seawater and stratified receiving water. Hydrates will affect mass transfer between CO_2 and seawater, and hence the elevation within the water column at which CO_2 is dissolved (Masutani *et al.*, 1995). Plume/ambient interaction will affect the elevation at which the CO_2-enriched seawater is ultimately sequestered and, in particular, whether or not the plume will impact more environmentally sensitive benthic organisms.

- Ocean circulation and mixing. Mortality of marine organism in the near field (<25 km from the injection point) has been shown to be very sensitive to horizontal diffusivity (Caulfield, 1996), yet most available data are from near surface experiments. Better quantification of vertical mixing is also needed because such mixing helps control the residence time of CO_2 within the water column. To help in site selection and to better understand sequestration times, it is important to further the development, intercomparison, and field validation of three-dimensional circulation models for the far field (>300 km from the injection point), including better ways to couple regional and global scale models.

- Biological impacts. Environmental assessments to-date have been based on bioassays using surface organisms exposed to constant levels of pH. More tests are needed on organisms found at depths of order 1000 m, and with time-varying exposure. Also, data are required to evaluate chronic effects of existing and potential future trends in varying pH.

- Ocean engineering. The feasibility of laying deep CO_2 pipelines (greater than 1000 m) or towing pipes from a moving ship has yet to be demonstrated. Such demonstration might allow discharge scenarios with less environmental impact and greater sequestration potential to be realized.

Many of these issues will require a combination of experimental and theoretical research. Laboratory research has progressed remarkably well over the last six years, especially in Japan (Ohsumi, 1995). However, many of the important physical, chemical and biological processes cannot be scaled, which means that more experimental research must eventually be conducted in the field. We believe this research should take place in three steps:

- small scale, short-term tests of physical/chemical perturbations conducted at an open ocean site. The US DOE is currently engaged in the planning of such an experiment -- a month-long field study conducted in collaboration with the Japanese at an open site such as the Kona coast of Hawaii.

- longer-term tests of acute and chronic biological impacts conducted at a semi-enclosed site such as a fjord.

- full scale testing using a prototype power plant outfitted for CO_2 capture.

Direct Utilization Technologies. Although utilization does not seem to offer large scale opportunities for mitigation, it is important to recognize that a large number of small uses can play an important part of an overall mitigation strategy. Further, if CO_2 can be used as a feedstock for useful products, it provides a credit against capture costs and avoids incurring land or ocean sequestration costs. An overview of the status of utilization opportunities at present is:

- Many diverse industrial niche opportunities exist for use of power plant CO_2, for linking of industrial processes to minimize CO_2 emissions, or for inexpensive capture of CO_2-rich streams.

- Increased production of hydrogen for use as a fuel offers additional inexpensive CO_2 capture opportunities.

- Microalgae conversion of CO_2 to biomass is the leading candidate for direct biological utilization of power plant CO_2 and has potential for significant improvements in conversion productivity.

- Longer term prospects for potential sequestration of power plant CO_2 as minerals are interesting but uncertain as to practicality.

- Large-scale conversion of power plant CO_2 to fuels, such as methanol, appears unattractive based on the criteria of effective energy utilization.

Future Activities

We are continuing to review relevant material for our report. The proceedings of The Third International Conference on Carbon Dioxide Removal (ICCDR-3) (Herzog, 1997) have just been published. This conference was hosted by the MIT Energy Laboratory with primary sponsorship of the US DOE and EPRI. The conference was held on September 9-11, 1996 and was attended by 250 delegates from 26 countries. These proceedings contain 111 papers divided into seven sections. All of this material is being reviewed in detail and will be summarized in our final assessment update report.

We are also collaborating with other efforts both nationally and internationally in this area, such as:

- ***A Workshop on Technological Opportunities for Fuels Decarbonization and Carbon Sequestration.*** Sponsored by the U.S. Department of Energy (FE, EE, and ER), this workshop is planned for July 28-30. Part of the objectives of this workshop directly overlap the objectives of the assessment update. Therefore, we are playing a major role in this workshop by being part of the organizing/program committee. Specifically, we are in charge of the break-out sessions on carbon sequestration. The results of this workshop will be incorporated into our assessment update.

- ***Climate Technology Initiative (CTI) Task Force 7.*** This international body is charged with fostering international collaboration in the area of carbon sequestration. It's research priorities are important inputs to the assessment update. We attended a major meeting of this task force on May 13-14 and plan to continue working closely with this task force.

We plan to have a draft report completed by this fall. This will then allow us to hold stakeholder meetings to solicit their inputs to the assessment before the end of this calendar year.

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