Environmental Protection

Carbon Sequestration: An Option for Mitigating Global Climate Change

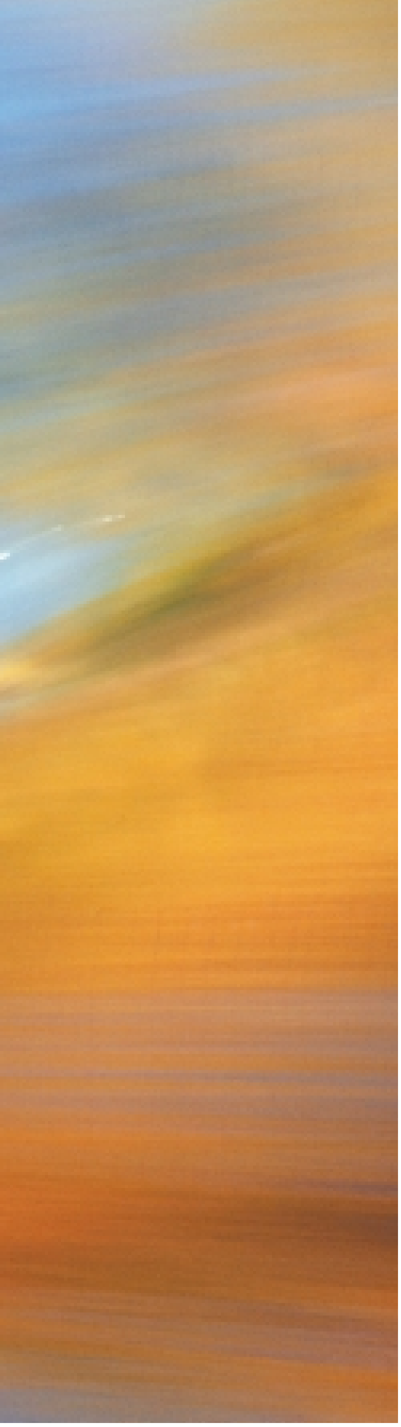
Robert L. Kane,
U.S. Dept. of Energy
Daniel E. Klein,
Twenty-First Strategies

Fossil fuels have been a major contributor to the high standard of living enjoyed by the industrialized world. However, possible requirements to reduce greenhouse gas (GHG) emissions may limit or alter their use in the future. The major greenhouse gas is carbon dioxide, and fossil energy combustion is the major source of anthropogenic (human-induced) CO_2.

Climate change is one of the primary environmental concerns of the 21st century. No single issue is as complex, or holds as many potential implications for the world's inhabitants. Our response to this issue could dictate fundamental changes in how we generate and use energy.

By 2020, the world's appetite for energy is likely to be about 75% higher than what it was in 1990, barring major changes in energy policies, environmental policies, and/or technologies *(1)*. Atmospheric concentrations of CO_2 are currently about 30% above pre-industrial levels and are rising. These rising concentrations are the focus of the United Nations Framework Convention on Climate Change (FCCC), which was ratified in 1992 and entered into force in 1994. The FCCC sets an "ultimate objective" of stabilizing "greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" *(2)*.

Many nations have begun taking actions to reduce or limit the growth of emissions of GHGs. Yet most reductions in *emissions* would still lead to increasing *concentrations* of CO_2 in the atmosphere, since we are emitting faster than our terrestrial and ocean sinks can absorb them. To stabilize atmospheric CO_2 concentrations, even



Greenhouse gases can be removed from exhaust streams or the atmosphere and stored so they cannot interact with the climate system. However, several challenges must be overcome before these technologies are technically and economically viable.

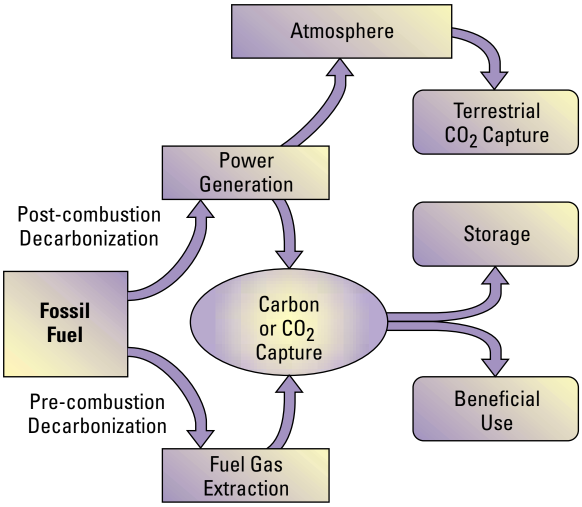
at double their current level, would require cutting global emissions by almost 70% relative to their 1990 levels.

The enormity of this challenge underscores the opportunities for new ideas and new technologies. Under assumptions of "business as usual," even factoring in anticipated trends in technologies and efficiencies, the direct costs of meeting long-term atmospheric concentration goals in the U.S. alone are measured in the hundreds of billions of dollars, and the worldwide costs are several times that amount. However, if advanced technologies can be developed and deployed, the total costs could be reduced by about half *(3)*. Hence, the opportunities — like the challenges — are also enormous.

This past March, in a letter to four Senators, President George W. Bush defined his Administration's policy regarding the reduction of CO_2 emissions from U.S. power plants. He cited "the lack of commercially available technologies for removing and storing carbon dioxide," and he said that the Administration would "continue to fully examine global climate change issues," with the goal of developing technologies and other creative ways to address global climate change.

The President's letter describes the difficulties inherent in balancing energy, environmental, and economic goals. At the same time, it highlights the opportunities that new technologies — such as carbon sequestration — can play in a comprehensive and balanced national energy policy.

This article explores the emerging science and technology of carbon sequestration. It outlines the roadmap developed by the U.S. Dept. of Energy (DOE) for government, industry, and academia to begin setting research and development (R&D) directions related to carbon sequestration. It explores several areas of research, as well as some of the chemical engineering challenges in this field.



■ Figure 1. What is carbon sequestration?

AIChE's 2002 Spring National Meeting (March 10–14) in New Orleans will include a special topical program addressing issues of CO_2 and greenhouse gases, including the role of carbon sequestration.

What is carbon sequestration?

There are three primary means to reduce CO_2 emissions associated with energy production without reducing economic output:

1. Improve the efficiency of energy conversion and end-use processes;
2. Shift to lower-carbon-content fuels (including noncarbon sources, such as renewable energy and nuclear power); and/or
3. Sequester the carbon released in energy production.

To reduce GHG emissions effectively and economically, we must be prepared to use all three of these methods. To date, most CO_2 mitigation strategies have focused on the first two, and these are considered by many to be the best and most cost-effective first steps in managing GHG emissions.

But while energy efficiency measures and low-carbon fuels can reduce emissions, it is questionable whether they are sufficient to stabilize CO_2 *concentrations*. Therefore, it is prudent to investigate the role that can be played by carbon sequestration.

Most people understand the term "carbon sequestration" to mean the uptake of CO_2 by trees and other plants through photosynthesis and their storing it as carbon for relatively short time periods. Another form of sequestration — injecting CO_2 into partially depleted oil reservoirs — is already underway to enhance oil production. CO_2 could also be injected into unmineable coal seams, thus enhancing the recovery of the coal-bed methane. However, these are only current examples of the many sequestration options that may someday be technologically and economically available.

More broadly, carbon sequestration is the removal of greenhouse gases either directly from the exhaust streams of industrial or utility plants or indirectly from the atmosphere, and storing them long-term so that they cannot interact with the climate system (Figure 1).

The DOE believes there may be new, innovative concepts for sequestration. The question is whether any of these ideas can be developed into practical, low-cost approaches.

A roadmap to develop carbon sequestration

Climate change is not a 10- or 20-yr challenge. It is a challenge measured in generations rather than years or even decades *(4)*. That is why long-term options must be considered. We must include — perhaps even concentrate on — options that offer progress toward stabilizing GHG concentrations on a global scale. A carbon sequestration strategy represents a long-term R&D approach that, if successfully developed, could offer a set of new options for dealing with GHGs, most likely in the post-2015 time frame.

Present technologies for carbon capture are not currently affordable, entail high energy penalties, and are limited in scope. To be viable, carbon sequestration will need to be less expensive, more efficient, and higher capacity. Accordingly, DOE has established the following program goals to guide its activities *(5):*

1. Provide economically competitive and environmentally safe options to offset all projected growth in base line emissions of GHGs by the U.S. after 2010, with offsets starting in 2015.
2. Achieve a long-term cost goal for carbon sequestration in the range of \$10/ton of avoided net costs.
3. Offset at least one-half the required reductions in global GHG emissions, measured as the difference between a business-as-usual base line and the emissions level corresponding to a concentration of 550 ppm CO_2, beginning in the year 2025.

DOE is developing a roadmap for setting R&D directions related to carbon sequestration. It drafted a report detailing the emerging science and technology of carbon sequestration *(6),* describing the research that DOE is examining in the following areas:

- system studies and assessments;
- enhanced natural sinks;
- capture and separations technology;
- geologic storage;
- ocean sequestration; and
- chemical and biological fixation and reuse.

Importantly, carbon sequestration is a concept that is both compatible with the current energy infrastructure *and* a bridge to future energy systems.

The major advantage of our present fossil-fuel-based energy system is, quite simply, that it works. It is relatively low cost. It uses low-cost and globally abundant resources. And it represents a huge capital investment in a global infrastructure. It will not be — nor should it be — discarded overnight *(7).*

Terrestrial sequestration

Terrestrial ecosystems include both vegetation and soils containing microbial and invertebrate communities. They are widely recognized as major biological "scrubbers" for CO_2. Terrestrial sequestration is defined as either the net removal of CO_2 from the atmosphere or the prevention of CO_2 emissions from leaving terrestrial ecosystems.

The terrestrial biosphere is estimated to sequester large amounts of carbon — about 2 billion m.t. annually. The total amount of carbon stored in soils and vegetation throughout the world is estimated to be roughly 2 trillion m.t. Hence, even a small change in the CO_2 flows could amount to large additional amounts sequestered.

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. Terrestrial sequestration can be enhanced in four ways:

1. reversing land use patterns;

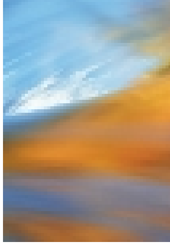


Table 1. Typical energy penalties due to CO_2 capture.

Power Plant Type	Today	Future
Conventional Coal	27–37%	15%
Gas	15–24%	10–11%
Advanced Coal	13–17%	9%

Sources: *(11, 12)*.

2. reducing the decomposition of organic matter;
3. increasing the photosynthetic carbon fixation of trees and other vegetation; and
4. creating energy offsets using biomass for fuels and other products.

This program area is focused on integrating measures for improving the full life-cycle carbon uptake of terrestrial ecosystems, including farmlands and forests, with fossil-fuel production and use. The efforts are being conducted in collaboration with the DOE Office of Science and the U.S. Forest Service.

Research is already underway. Ohio State Univ. (Columbus) and Virginia Polytechnic Institute (Blacksburg) are studying the use of soil enhancers made from the solid wastes of coal plants, paper mills, and sewage treatment facilities to improve the natural carbon uptake of lands disturbed by mining, highway construction, or poor management practices. The Stephen F. Austin State Univ. (Nacogdoches, TX) is evaluating a reclamation/reforestation program that would sequester carbon in trees on abandoned mine lands in the Appalachian region *(8, 9)*. These projects also demonstrate the multiple benefits that often accompany terrestrial sequestration in the form of improved soil and water quality, better wildlife habitats, increased water conservation, and the like.

CO_2 separation and capture

The idea of capturing CO_2 from the flue gases of power plants did not start with greenhouse gas concerns. Rather, it gained attention as a possible source of supply 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 thus the productivity of the reservoir. Several commercial CO_2 capture plants were constructed in the late 1970s and early 1980s in the U.S., but only one, the North American Chemical Plant in Trona, CA, which started operation in 1978, is still operating today.

CO_2 is generated as a byproduct of natural gas production. In general, gas fields contain up to 20% 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.

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). 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 *(10)*.

To date, all commercial plants to capture CO_2 from power-plant flue gas use processes based on chemical absorption with a monoethanolamine (MEA) solvent. MEA was developed over 60 years ago as a general, nonselective solvent to remove acid gases such as CO_2 and H_2S from natural gas streams. The process was modified to incorporate inhibitors to resist solvent degradation and equipment corrosion when applied to CO_2 capture from flue gas. Also, the solvent strength was kept relatively low, resulting in large equipment and high regeneration energy requirements *(11)*.

Therefore, 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 MWe (net) coal-fired power plant may be reduced to 400 MWe (net) after CO_2 capture, an "energy penalty" of 20%. 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 as it is projected to evolve in the next 10 to 20 years *(11, 12)*.

There are numerous options for the separation and capture of CO_2, many of which are commercially available. Many advanced methods are also under development, such as adsorbing CO_2 on zeolites or carbon-bonded activated fibers and then separating it using inorganic membranes *(13)*. However, none have been applied at the scale required as part of a CO_2 emissions mitigation strategy, nor has any method been demonstrated for a broad range of anthropogenic CO_2 sources. Additional research into advanced processes seeks to improve the potential of these options.

Several major studies have analyzed the economics of capturing CO_2 from the flue gas of coal-fired power plants (Table 2). These studies looked at CO_2 capture from pulverized coal (PC) power plants and from integrated gasification combined cycle (IGCC) power plants. MEA scrubbing was used in the PC plants, whereas IGCC plants allowed the use of more energy-efficient scrubbing processes involving physical absorption. All studies used commercially available technology and included the cost of compressing the captured CO_2 to about 2,000 psia for pipeline transportation *(14–19)*.

For PC plants, the cost of reducing CO_2 emissions is in the range of about \$30–70/m.t. of CO_2 avoided. For IGCC plants, the cost of reducing CO_2 emissions is about \$20–30/m.t. These costs exclude storage, which might add an additional \$5–15/m.t.

In general, these findings are very encouraging. Al-

Table 2. Comparison of CO_2 capture costs.

Study	Argonne *(14)*	EPRI *(15)*	Utrecht *(16)*	IEA GHG *(17)*	EPRI *(18)*	Utrecht *(16)*	Fluor *(19)*
Plant Type	IGCC	IGCC	IGCC	IGCC	PC	PC	PC
CO_2 Reduction							
CO_2 emitted without capture (kg/kWh)	0.80	0.87	0.80	0.78	0.91	0.80	0.91
CO_2 emitted with capture (kg/kWh)	0.20	0.10	0.10	0.17	0.14	0.10	0.14
Reduction in CO_2 emissions	75%	88%	88%	78%	85%	88%	85%
Energy Penalty							
Plant efficiency (HHV) without capture	37%	36%	44%	40%	35%	41%	35%
Plant efficiency (HHV) with capture	33%	29%	36%	34%	23%	32%	24%
Energy penalty	9%	19%	17%	15%	34%	23%	31%
Cost of capture							
Efffective capital charge rate	11%	13%	7%	9%	12%	7%	12%
Electricity price without capture (¢/kWh)	5.8	5.7	3.8	5.9	4.6	3.7	4.6
Electricity price with capture (¢/kWh)	7.1	8.2	5.1	7.6	10.1	6.1	9.4
Increase in price	22%	44%	34%	29%	120%	65%	104%
Cost of capture (\$/m.t. CO_2 avoided)	\$21	\$32	\$18	\$29	\$72	\$33	\$62

Note: The studies use different years' dollars in their costing. The precision that might be gained by converting these estimates to the same year's dollars is small relative to the uncertainty inherent in and across these cost estimates.

Sources: *(14–19)* as cited in *(12)*.

Table 3. Worldwide potential of geologic CO_2 storage.

	Approximate Global Capacity	
Storage Option	**CO_2, billion m.t.**	**Portion of Emissions through 2050**
Deep Saline Reservoirs	400–10,000	20–500%
Depleted Oil and Gas Field	920	45%
Unminable Coal Seams	15+	1+%

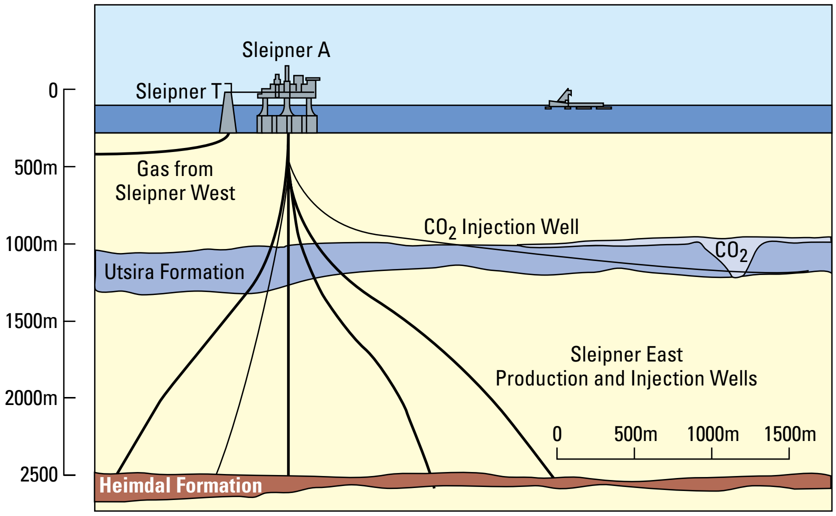
Source: *(20)*.

ready, in Norway, under an existing carbon tax, a power plant with CO_2 capture for sequestration is scheduled to be built within the next few years.

However, the viability of CO_2 capture from power plants should not be judged based on today's relatively expensive technology. There is great potential for technological improvements that can significantly lower costs. For example, improving the heat rate of fossil plants or reducing the energy penalty for CO_2 capture could significantly reduce costs. For coal-fired power plants, achieving a 50% thermal efficiency (*i.e.*, a 30% decrease in heat rates) would result in a 30% decrease in capture costs alone. As Table 1 suggests, the energy penalty could be cut in half with only evolutionary developments, thereby cutting capture costs about 40%.

R&D is required to help fill the many gaps in the science and technology. Challenges exist in the areas of chemical and physical absorption and adsorption, low-temperature distillation, gas-separation membranes, and product treatment and conversion. Research will be needed to achieve the desired breakthroughs in cost, efficiency, and safety.

Several DOE projects are seeking technologies that can lower the costs and improve the separation of CO_2 from the gas streams of energy facilities and other sources *(8, 9)*. Los Alamos National Laboratory (Los Alamos, NM) and Idaho National Engineering and Environmental Laboratory (Idaho Falls) will collaborate with the Univ. of Colorado (Boulder), Pall Corp. (East



Source: *(22)*.

Figure 2. The Sleipner CO_2 injection project.

Hills, NY), and Shell Oil Co. (Houston, TX) to develop an improved high-temperature polymer membrane for separating CO_2 from methane and nitrogen gas streams. Media and Process Technology Co. (Pittsburgh, PA) is developing a high-temperature CO_2-selective membrane as a reactor, which can enhance the water-gas shift reaction efficiency while recovering CO_2 simultaneously for sequestration in IGCC power generation systems. Research Triangle Institute (Research Triangle Park, NC) is developing a simple, low-cost CO_2 separation technology with a reusable, sodium-based sorbent to capture CO_2 from the flue gas of existing fossil-fuel combustion sources.

Geologic sequestration options

Once captured, CO_2 needs to be sequestered. There are a variety of potential geologic sequestration options for long-term storage. This is not really a new concept. For example, CO_2 is currently injected into more than 70 operating oil fields to enhance oil production. What is new is the idea that storage of CO_2 is a desirable goal in and of itself.

As seen in Table 3 *(20),* the storage potential of these geologic options is enormous, possibly measured in trillions of m.t. This is many times larger than total worldwide energy-related CO_2 emissions, estimated at about 22.6 billion m.t. of CO_2 in 1997 *(1).*

Deep saline reservoirs may be the best long-term underground storage option. Such reservoirs normally are too salty to provide potable water supplies, and are generally hydraulically separate from shallower reservoirs and surface water. Depending on the reservoir, injected CO_2 would displace the saline water, with some of the CO_2 dissolving, some reacting with the solids, and some remaining as pure CO_2. Deep saline reservoirs are located throughout much of the U.S., so perhaps 65% of the CO_2 emitted from U.S. power plants could be injected into them without the need for long pipelines. In the U.S. alone, the estimated storage potential of deep saline reservoirs ranges from 5 to 500 billion m.t. of CO_2.

There is already considerable experience with the use of deep saline reservoirs for storing large quantities of fluids. Over 167,000 oil and gas injection wells inject over about 2.5 billion m.t./yr *(21),* and over 9 billion gal/yr, or 33 million m.t./yr, of hazardous wastes are injected into wells.

The first commercial CO_2 capture and sequestration facility began in September 1996, when Statoil of Norway began storing CO_2 from the Sleipner West gas field in a sandstone formation 1,000 m beneath the North Sea. This CO_2 derives from the natural gas processing, where the CO_2 content of the extracted natural gas needs to be reduced from 9.5% to 2.5%. The economic incentive for this project is the Norwegian carbon tax (currently \$38/m.t. CO_2).

Instead of being vented, the captured CO_2 is injected from a floating rig through five pipes at a rate of 20,000 m.t./wk, as shown in Figure 2 *(22).* (This corresponds to the rate of CO_2 produced from a 140 MWe 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. The cost of the operation is said to be approximately \$15/m.t. of CO_2 avoided.

Preliminary hydrogeologic and geochemical modeling showed that there is enormous potential for CO_2 sequestration in the midwestern U.S., especially in the Mt. Simon sandstone. This capacity appears to be sufficient for storing emissions for several decades or more. However, the modeling also indicated that local factors, such as formation thickness, permeability, injectivity, and geochemistry, significantly influence the technical feasibility and cost effectiveness of this technology. Accordingly, site-specific assessments will be an important step in better understanding this regional capacity. A realistic pilot test over a year or more would enable this concept to move beyond the laboratory and computer simulation stage.

Depleted oil and gas reservoirs also appear to be a promising land storage option. Because they have previously contained hydrocarbon gases for thousands of years, their geologic integrity is likely to be good. In the U.S., currently abandoned oil and gas reservoirs could hold about 3 billion m.t. of CO_2. Over time, as the U.S. draws more oil and gas from its reservoirs, the inventory of depleted reservoirs will increase. The ultimate CO_2 storage capacity for the U.S. could be around 100 billion m.t. of CO_2. Several issues must be resolved, however, before these can be considered viable candidates for CO_2 storage.

In southern Saskatchewan, PanCanadian Petroleum is developing the Weyburn CO_2 EOR project, which began operation in the fall of 2000. In addition to extending the life of this field by another 25 years, the project provides an excellent opportunity for developing an understanding of how CO_2 is stored underground. Since the field is relatively shallow and has been extensively developed, there are numerous observation wells and a comprehensive understanding of the geology of the field. It is estimated that about half of the injected CO_2 will be locked up in the oil that remains in the ground, and that over the 20-yr lifetime of the project, about 19 million m.t. of CO_2 will be stored *(23)*. By developing an understanding of the fate of the CO_2 in the oil reservior, confidence in EOR as a CO_2 storage option can grow.

Abandoned or uneconomic coal seams could also become CO_2 storage sites, because CO_2 injected into coal adheres to the coal surface and remains within the seam. Some of the early research regarding CO_2 storage in deep coal seams is particularly intriguing because many coal deposits contain methane — itself a potent GHG. The injected CO_2 displaces the sorbed methane from the coal surface, with two molecules of CO_2 being trapped for each molecule of methane released *(24)*. By injecting waste CO_2 into methane-rich unmineable coal deposits, more methane is produced for energy.

U.S. coalbed methane production is largely concentrated in the southwestern San Juan Basin and Alabama's Black Warrior Basin. About 8 billion m.t. of CO_2 sequestration potential is contained in the San Juan Basin, along with enhanced recovery of the methane *(25)*. Worldwide, storage potential is estimated to be upwards of 150 billion m.t.

CO_2-enhanced coalbed methane recovery is being tested in the vast, deep coalbeds in Alberta, Canada. In a process called enhanced gas recovery (EGR), CO_2 is injected into deep, unmineable coalbeds to recover methane *(26)*. The initial phases of the project, led by the Alberta Research Council, have been favorable, and the effort is now moving into the design and implementation of a full-scale pilot project. Injection began in 2000 and will continue for 12 months; if successful, full-scale development can begin in 2002.

Several DOE projects are directed at identifying and resolving technical and environmental issues in seques-

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tering CO_2 in a variety of geological formations *(9)*. Advanced Resources International (Houston, TX) is planning to demonstrate CO_2 sequestration in deep unmineable coal seams in the San Juan Basin using enhanced coalbed methane recovery. Texas Tech Univ. (Lubbock) is creating a novel well-logging technique using nuclear-magnetic resonance to characterize the geologic formation for long-term CO_2 storage, including the integrity and quality of the reservoir seal. The Univ. of Utah (Salt Lake City) is identifying the geochemical reactions in natural CO_2 fields in deep saline reservoirs, which are analogues for repositories of CO_2 separated from the flue gases of power plants.

Ocean sequestration

The world's oceans may be a large potential sink for anthropogenic CO_2 emissions. However, because the oceans play such an important role in sustaining the biosphere, any potential changes to these ecosystem functions must be carefully and thoroughly considered. We currently have very little knowledge of how the potential pH change or other impacts due to CO_2 injection would affect the biogeochemistry and ecosystems in the deep ocean. Improvements in understanding marine systems are needed before marine sequestration could be implemented on a large scale.

An initial test of deep-sea CO_2 release has provided promising findings *(27, 28)*. A remote-operated vehicle was used to drip a small amount of liquid CO_2 into a 4-L laboratory beaker on the ocean floor, roughly 2 miles below the surface. At this depth, the CO_2 has a higher density than seawater, and sinks rather than rises. The CO_2 quickly combined with water to form a block of ice-like hydrate. It is expected that the hydrate would dissolve very slowly, which would minimize local concentration effects. Observations of nearby fish activity suggested that biological impacts would be small.

More tests of deep-sea carbon sequestration are scheduled, including one late this year or early next year off the coast of Kona, Hawaii. In the proposed CO_2 Ocean Sequestration Field Experiment, a multinational group of researchers plans to inject about 40–60 tons of pure liquid CO_2 into ocean waters nearly 3,000 ft deep over a period of about 2 weeks *(29)*. The goals of this experiment are to gather data in the vicinity of the CO_2 injection point to improve our understanding of the basic physical phenomena, and to use this in refining computer models to estimate potential environmental impacts.

To implement ocean CO_2 sequestration on a larger scale, several methods of injection have been proposed. One method is to transport the liquid CO_2 from shore via a pipeline and to discharge it from a manifold lying on the ocean bottom, forming a rising droplet plume. Another method is to transport the liquid CO_2 by tanker

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and then discharge it from a pipe towed by the moving ship. Still another approach is to inject the CO_2 as deeply as possible in order to maximize the sequestration efficiency. One such idea is to inject the liquid CO_2 to a sea floor depression, forming a stable “deep lake” at a depth of about 4,000 m.

Chemical and biological fixation and reuse

The goal of CO_2 utilization is to design chemical processes that can convert CO_2 to useful and durable products that have reasonable lifetimes. While storing CO_2 can mitigate the GHG problem, converting CO_2 to useful products can create additional economic and environmental benefits.

Research in advanced chemical and biological sequestration is aimed at permanent, stable sequestration, and at recycling carbon to create new fuels, chemical feedstocks, and other products. Three possible end uses include particulate carbon in composite materials and construction materials, CO_2 as a feedstock for production of plastics, and carbon to create soil amendments.

Advanced chemical processes might lead to unique sequestration technologies or to improvements in our understanding of chemistry that will enhance the performance of other sequestration approaches. Advanced chemical technologies envisioned for the future would work with the technologies now being developed to convert recovered CO_2 economically into benign, inert, long-lived materials that can be contained and/or have commercial value.

Advanced biological processes can augment or improve natural biological processes for carbon sequestration from the atmosphere in terrestrial plants, aquatic photosynthetic species, and soil and other microbial communities. These technologies encompass the use of novel organisms, designed biological systems, and genetic improvements in metabolic networks in terrestrial and marine microbial, plant, and animal species.

All concepts for these technologies are at an early research stage. Better understanding of the basic processes and new chemistry and bioprocessing approaches is needed before practical, achievable technology performance or cost levels can be estimated.

DOE projects in this area are directed at exploring novel chemical or biological methods for converting CO_2 into either commercial products or into inert, long-lived stable compounds *(8, 9)*. Idaho National Engineering and Environmental Laboratory is teaming with Montana State Univ. (Bozeman) and the Univ. of Memphis to study ways to grow microorganisms known as cyanobacteria as “biofilms” that could capture and convert CO_2 through photosynthesis. Researchers at Ohio Univ. (Athens) are developing a novel biologically based process to reduce CO_2 emissions, attaching photosynthetic organisms to specially designed growth surfaces arranged in a bioreactor to minimize pressure drop and create a near-optimal enhanced photosynthetic process. Physical Sciences, Inc. (Andover, MA) is developing technologies for CO_2 recovery and sequestration by photosynthesis of micro-algae, demonstrating the ability of selected species of micro-algae to effectively fix carbon from typical power plant exhaust gases.

Concluding thoughts

To limit the costs of reducing emissions of greenhouse gases, many technological options will be needed. To have these technological options available when we need them in the future, we need to be doing research today.

Carbon capture and sequestration is an area with great potential. Its potential benefits for our energy systems and our global environment are too great to ignore, and warrant our best efforts to get it started right.

Chemistry and chemical engineering are key to research breakthroughs in carbon sequestration. Advances in chemical sciences and the resulting technologies will enable CO_2 to be captured in greater quantities and at lower cost. Understanding the chemical interactions of CO_2 in underground and ocean environments will help us assess the longer-term fate and ultimate acceptability of these promising storage options. The transformation of CO_2 into materials with potential commercial value is a field in its infancy, but may ultimately lead to the best uses of our planet’s rich fossil-fuel resources.

The challenges may be great, but the rewards could be vastly greater. **CEP**

R. L. KANE is the Global Climate Change (GCC) Issue Manager in the DOE’s Office of Planning and Environmental Analysis, Office of Coal and Power Systems in the Office of Fossil Energy (FE), Washington, DC (Phone: (202) 586-4753; Fax: (202) 586-188; E-mail: robert.kane@hq.doe.gov). His responsibilities include management of GCC activities and assessing the impacts of domestic and international GCC initiatives on the fossil energy program. He also coordinates FE’s activities in the area of carbon sequestration, and on the Climate Challenge program, a highly successful voluntary emission-reduction program with the electric utility industry. He holds a BS in meterology from Penn State Univ. and an MS in air resources management from the Univ. of Pittsburgh.

D. E. KLEIN is president of Twenty-First Strategies, McLean, VA (Phone: (703) 893-8333; Fax: (703) 893-8813; E-mail: dklein@21st-strategies.com), which he founded in 1995 to offer energy and environmental consulting services to utilities, government agencies, and others. He has 25 years of consulting experience in energy, environmental, and economic analysis, and he has conducted hundreds of projects related to electric utility fuel use, coal supply, transportation, antitrust issues, and related environmental concerns. His work in recent years has focused on climate change issues, both on policy and programs from the government side, as well as strategies for the private sector. He earned a BS in urban studies from Massachusetes Institute of Technology and an MBA from the Stanford Univ. Graduate School of Business.