9 STAKEHOLDER PERSPECTIVES

Vision

An effective carbon sequestration R&D program will require interagency cooperation and partnership with industry and nongovernmental organizations to ensure that scientific innovation leads to practical application.

"Removing carbon dioxide from the atmosphere is as important as controlling emissions. Basic and applied research need to be pursued in the face of political obstacles. Alongside attempts to limit mankind's production of greenhouse gases, there is a pressing need to find ways of removing carbon from the atmosphere and 'sequestering' it in the land, in geological formations and in the oceans. The government has now taken laudable steps in that direction . . . At a DOE workshop on sequestration last week, researchers were bullish about ocean and geological sequestration research. More positively still, there is an encouraging level of cooperation between the agency's Office of Science and Office of Fossil Energy—offices that haven't always had a smooth working relationship. But on sequestration, the Office of Science's orientation towards more basic research appears to fit well alongside the more applied outlook of the Office of Fossil Energy. Such cooperation will be necessary to lead the way as the complexities and costs of sequestration become better understood. This cooperative attitude must also extend to the partnerships between scientists and industry if large-scale sequestration is to be made reality." (*Nature* 401; Sept. 23, 1999; www.nature.com).

No one can ensure today that in 10, 20, or 30 years carbon sequestration will be the answer — or one of the answers — to the problem of global climate change. No one can predict whether in 20 or 30 years the world will embrace fossil fuels as future fuels, enjoying their benefits and discarding concerns over their impacts on the world's climate. We hope to agree that this is an area with enough significance— and enough potential to ultimately affect every person on this planet — to warrant making our best effort to get it started right.

Following through on DOE's intent to include in the development of its carbon sequestration research program a broad diversity of stakeholder perspectives, a Carbon Sequestration Stakeholders Workshop was held on September 14–15, 1999, in

Gaithersburg, Maryland. DOE used a team of about 70 technical specialists from its national laboratories, academia, industry, and other federal agencies to organize and develop the first draft of this report on *Carbon Sequestration Research and Development,* distributed in February 1999. That report served as the basis for dialog at this workshop.

The workshop had several goals. In a speech in June 1999, Secretary Richardson emphasized that carbon sequestration is an important third option in DOE's climate portfolio. He also asked for help in putting together a program that made sense (Richardson 1999). DOE wanted to attract the attention of the best minds in the business and obtain a critical review of the first draft of this report from a broader community of experts than were involved in the writing of the draft report. Advice, based on other research programs and experience, was needed to refine DOE's research agenda. The development of a community of carbon sequestration researchers would be useful, and this workshop could help improve the necessary collaborations, partnerships, and common understandings.

DOE used this Stakeholders Workshop to obtain feedback from the technical and commercial sectors on the contents of its carbon sequestration research plan, as described in this report. The potential contributions of scientific innovation and the application needs of industry were examined. Advice was collected from attendees on their perspectives for priorities for the R&D program. This was an opportunity to ascertain what other researchers were thinking, to see what industry was doing relative to CO_2 emission reductions and sequestration, and to learn how nongovernmental organizations were approaching carbon sequestration options. Most important, this workshop started the process of building collaborations and forming partnerships among stakeholders.

Promoting a new area of technical endeavor, such as carbon sequestration, is a process of collection and maturation of innovative ideas. This workshop serves as a starting point for DOE to develop the interest of a community of researchers who would devote their creative thinking to address the challenges of carbon sequestration.

The workshop was opened with introductory remarks by Martha Krebs, Director of DOE's Office of Science, and Robert Kripowicz, Principal Deputy Assistant Secretary of the Office of Fossil Energy. They discussed DOE's approach to carbon sequestration research, from its most basic principles to its most practical applications, and noted that this broad spectrum of research, in turn, will require close intra- and inter-agency as well as external coordination and cooperation.

The plenary sessions were organized around speakers who represented their own views and, as well as possible, various stakeholder groups: the international nongovernmental sector, the research community, the environmental community, and the energy industry. Breakout groups, organized around sequestration options, provided an arena for discussion and input to the report. They included sessions on separation and capture, ocean sequestration, sequestration in terrestrial ecosystems, sequestration in geological systems, and advanced concepts (biological and chemical) for carbon sequestration.

Reports from the plenary sessions and the breakout groups are presented beginning on page 9-7 of this chapter.

9.1 POINTS COMMUNICATED TO DOE AT THE WORKSHOP

Participants at the Stakeholders Workshop largely affirmed the direction of DOE's effort. Participants urged the use of collaboration and partnerships in conducting R&D to ensure the best use of research funds and avoid duplication of effort. R&D priorities for research planning were suggested. Much of the discussion focused on the necessity to integrate R&D efforts with developments in various energy technology systems and to understand the environmental impacts of sequestration technologies.

Collaborative Programs

Several federal agencies currently fund programs related either directly or indirectly to carbon sequestration. The carbon cycle science program in the U. S. Global Change Research Program includes DOE, USDA, NSF, NASA, the National Oceanic and Atmospheric Administration, and the USGS. In addition, the Department of Defense Office of Naval Research and the Environmental Protection Agency have programs in carbon sequestration or other related areas. The IEA has sponsored research on carbon sequestration for many years.

The private sector is actively involved in geologic sequestration as applied to enhanced oil recovery, CO_2 separation, and other sequestration activities. A number of international programs involve carbon sequestration, including ocean sequestration research funded by Japan, Norway, the United States, and the United Nations Environmental Program. Several geological sequestration programs are under way, such as the IEA-endorsed Pan Canadian Resources project at Weyburn in Saskatchewan and the Statoil project at Sleipner in the North Sea. Participants counseled DOE to be proactive in integrating its activities with these other programs wherever possible to optimize the use of programmatic funds.

Priority Setting

The priorities identified by the participants track potential benefits and problems associated with specific technologies. The magnitude of the potential benefits to be derived from a technology is important, such as the potential amount of CO_2 to be sequestered. So is the difference in residence times of carbon (i.e., how long CO_2 can be sequestered) offered by competing technologies. Finally, any market benefit to be derived from development of a technology, such as enhanced oil recovery or production of new carbon-based industrial materials, may offer the opportunity for nearer-term technology commercialization and implementation. Because the effectiveness of sequestration methods needs to be verified, it is important to develop new or improved analytical instrumentation and monitoring technologies to measure the efficacy of various approaches.

Priorities will depend on a better understanding of the impacts of sequestration implementation on the environment. In addition, operational uncertainties must be reduced so that future costs and financial risk can be determined. Part of the uncertainty analysis must include life cycle analysis for the components of a particular process. In particular, certain enabling activities, such as gas compression and transportation systems, have not been evaluated in the detail needed. Most participants also agreed that socioeconomic impacts and societal perceptions of risk must be addressed and that the public must be properly informed as to the nature of sequestration projects.

A Systems Approach

Options to address climate change include a wide variety of technologies and practices, such as improved efficiency; nuclear, renewable, and fossil energy; and sequestration. Consequently, an analysis of sequestration cannot be separated from a wider system of energy supply and use. Furthermore, some sequestration options, such as capture and separation, are intimately tied to advances in other specific technologies, such as new power plant designs.

Integration of carbon sequestration R&D efforts should continue to consider system technology platforms highlighted in Chap. 8: carbon processing, biological absorption, engineered injection, and advanced characterization and monitoring technologies.

All breakout sessions agreed that a better understanding of environmental impacts is critical. Although we are starting to recognize that emitting CO_2 into the atmosphere may lead to a changed global climate, there are few analyses describing potential impacts of sequestering it in the terrestrial or oceanic biosphere or in geologic formations. Thus researchers need to design or leverage experiments that examine environmental impacts as part of larger engineering studies. Any environmentally based experiment should be systems-based to enable greater understanding of related, unanticipated impacts and of ecosystem dynamics. Greater understanding of a number of coupled biogeochemical cycles (e.g., water, oxygen, nitrogen) is required for adequate understanding of the carbon cycle. All breakout groups saw the need for innovative, improved, and more sensitive analytical instrumentation and monitoring technologies.

The organization of existing data and the careful design of future data collection should be a priority. The ocean, geological, and terrestrial groups agreed on the importance of a digital environmental atlas and suggested DOE, NASA, USGS, and USDA as agencies that might appropriately collaborate on such an effort.

The need for systems integration is particularly relevant for capture and separation technologies coupled to direct injection of CO_2 into oceans or geologic settings. Life cycle analysis would help ensure that all costs, impacts, and benefits are properly included. Additionally, the degree of separation and purification of gases may strongly affect cost. It may be possible to dispose of gaseous mixtures in which CO_2 is not of high purity in order to save costs associated with capture and separation technologies.

The magnitude of the problem and possible solution pathways requires a portfolio approach. Some technologies are commercially viable now because of uses other than sequestration, but their high costs mean that their utility may be limited. Large-scale breakthroughs will require considerable scientific and engineering innovation. That is the integrating theme of the advanced concepts breakout session. All of those approaches could naturally fit into one of the other groups. However, this group focused on breakthrough concepts where research should be funded to “change the rules of the games” because of the magnitude of the problem. We must capitalize on exogenous R&D for near-term commercial successes. We must build on laboratory-based research to develop new field experiments and pilot activities. And we must draw on all of these activities to develop breakthrough technologies in order to have a significant sequestration effect on fossil fuel emissions by 2025.

9.2 A RADICAL APPROACH TO GLOBAL WARMING

> *The bland suburban hotel held a sea of gray and balding heads. They belonged to scientists and engineers, who, by and large, were unfashionably dressed . . . It was, in short, a gathering of nerds. But these were nerds who may hold our future in their hands. The turnout was robust at a recent two-day Energy Department workshop intended to help chart a road map for conducting research on the idea of carbon sequestration* . (Solomon, October 2, 1999, *National Journal*).

The challenge being addressed is how to turn the scientific potential of carbon sequestration into reality. This chapter summarizes the views of scientists, industry, environmentalists, and government officials on DOE's draft *Carbon Sequestration Research and Development* report and provides guidance in developing R&D for practical carbon sequestration technologies. The atmosphere at the workshop was one of encouragement and cooperation, recognizing that some solutions using new forms of sequestration with larger-scale field applications will take decades. This is a technical challenge that DOE is ideally suited to help undertake. Input from the stakeholder community has been helpful to DOE, especially in identifying promising options and in establishing R&D priorities. This guidance has been incorporated into the technical chapters of this report, and key perspectives and issues raised by the user community have been highlighted in this chapter. The next steps will be to focus on each of the carbon sequestration elements (Chapters 2–7) and work on setting R&D priorities within elements. Even now, we have identified a number of promising carbon sequestration options, and research directions have been established. Recommendations for proceeding with a carbon sequestration R&D program are summarized in Chapter 10 of this report.

Reports from the Plenary Sessions and the Breakout Groups

Carbon Sequestration Stakeholders Workshop
Gaithersburg, Maryland
September 1999

Carbon Sequestration Stakeholders Workshop
Gaithersburg, Maryland
September 1999

THE PLENARY SPEAKERS

International Perspectives on Carbon Sequestration[1]

The International Energy Agency is one of the leading international, nongovernmental organizations. Its proactive Greenhouse Gas R&D program provides important information on greenhouse gas emissions and carbon sequestration (Eds.).

International collaboration for developing carbon sequestration technology
It is widely accepted that sequestration is likely to be an important option for dealing with climate change in the 21st century. There has been a significant change in attitude toward this subject in the past few years, in response to these developments:

- recognition that something will need to be done about the changing climate
- growing understanding that fossil fuels will continue to play a role in energy supply for many years to come, so we will need ways of making them climate-friendly
- acceptance that what is needed is a large-scale solution, which carbon sequestration can provide and can deliver through the use of known technology
- understanding that R&D, leading to demonstrated technology, provides insurance against the more severe outcomes of climate change

As a result, many more people are interested in knowing what the sequestration technologies can do, how they can be improved, and the best ways to use them.

In the next 100 years, there will be a large and growing gap between actual emissions (in a business-as-usual scenario) and the level of emissions that would stabilize atmospheric CO_2 levels. If the world might turn out anything like the projections made by some climate change researchers, we will need options to avoid damaging climate change. Especially after the first Kyoto commitment period, options that can deliver deep (60 to 70%) reductions in emissions may be needed, which include sequestration. So sequestration technologies could play an important role, but there is still room for them to be improved. That is the reason for this workshop.

Identifying targets for research and development
The IEA Greenhouse Gas R&D Programme (IEA GHG) (http://www. ieagreen.org.uk) has been working on carbon sequestration technologies for 8 years. The Programme is an international collaboration of 17 countries and more than 20 industrial organizations, 7 of whom are direct sponsors. It has three main objectives:

- to evaluate technologies for reducing emissions, especially from use of fossil fuels
- to disseminate the information obtained
- to identify targets for necessary R&D and promote action

[1] This plenary presentation of the Carbon Sequestration Workshop was made by Dr. Paul Freund of the International Energy Agency.

IEA GHG has conducted about 80 studies covering all stages of sequestration technology, from capture of CO_2 from flue gas streams in power plants and other major process plants, to CO_2 storage, to utilization of CO_2 in various ways, to enhancement of natural sinks by methods such as afforestation or fertilization of the ocean, to production of hydrogen from fossil fuels with sequestration of CO_2, as well as many other mitigation options.[2]

These studies have identified much work that needs to be done in research, development, or demonstration. For example, IEA GHG's expert workshops have defined research priorities in areas such as ocean storage of CO_2. The recommendations of these workshops cover many different aspects, including the need to (1) increase our confidence in predicting how long it will take CO_2 to return to the atmosphere, (2) understand and minimize environmental impacts, (3) take account of the legal position and likely public attitudes, and (4) gain practical experience.

IEA is following up on these recommendations in many ways, including a series of forums to encourage international stake-holder dialogue. Equally important for research planning purposes is to know what not to do. In this light, here are some of the important targets for research:

- Capture of CO_2—The cost and energy consumption of capture presents a major barrier to early adoption of sequestration technology. There is a need to reduce the cost markedly and improve the energy efficiency of the separation process; to ensure stable and long-lived solvents; and, for the longer term, to consider more radical changes in the systems.

- Storage (sequestration) of CO_2—Important goals are to build confidence and win acceptance of the concept (which requires demonstrating reliable and safe operation in as many individual examples as possible); ensure low environmental impact; and, at a more practical level, identify potential reservoirs at local levels, calibrate predictive models, develop methods of verification, and address legality. Utilization options such as enhanced oil recovery and CO_2-enhanced recovery of coal bed methane are essentially storage options, so the same requirements apply to them.

- Utilization of CO_2—Using CO_2 to make things, such as chemicals or materials, must achieve a net reduction in emissions; to do so, the proposed schemes must pass tests of thermodynamics and energy requirements. There are more practical requirements, too, such as the length of time the CO_2 will be sequestered, the size of the market, and cost. So far, we have not found uses of CO_2 for making chemicals or materials that pass these tests, so this challenge for research is a tough one.

- Additional research areas, such as CO_2 transport and enhancement of natural sinks.

There is still enough time to bring forward radical new ideas on ways of doing things such as separating CO_2. Results of exploratory research should then be assessed to identify those that could deliver large prizes—those particular ideas would warrant further development.

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[2] The 5th international conference on greenhouse gas control technologies will be held in Cairns, Australia, in the year 2000. The call for papers for this conference will be distributed shortly.

Collaborative research and development projects

In a situation where there is more work to be done than resources available, collaboration is an obvious approach; it is even more obvious for tasks such as carbon sequestration where there is only limited opportunity for competitive advantage, especially among users of the technology. Where there are unique facilities for learning, collaboration is especially important to allow many people to take advantage of them. With the world facing a global problem in climate change, international collaboration is an important tool for research.

A number of practical R&D projects organized as international collaborations are already under way: IEA GHG assists most of these in some way:
- Sleipner deep saline reservoir
- Alberta enhanced coal bed methane project
- Canadian O_2/CO_2–recycle combustion
- Weyburn enhanced oil recovery monitoring
- Ocean storage project in Hawaii

Others are in planning:
- BP Amoco Schrader Bluff joint industry project
- Precombustion decarbonization demonstration plant (IEA GHG)
- Catalytic flow reversal reactor to tackle dilute methane emissions (Canada)

Sleipner is a unique facility—it hosts the world's first commercial-scale project for geological sequestration of CO_2. Statoil began work on this project in the early 1990s, for commissioning in 1996. It became apparent that Sleipner presented a unique opportunity for a research and monitoring program. IEA GHG helped to bring together international participants in a collaborative research project, helped develop research priorities, and took the lead in discussions with Statoil. These discussions continued for two years and eventually culminated in a three-phase plan:

- Phase 0, collection of baseline data, is complete.
- Phase 1, a partially European-funded project to monitor the reservoir, includes a seismic survey of the reservoir that is under way.
- Phase 2, an international research and monitoring project to build on this work, is being put together now. Many of the participants in this workshop may want to join in.

This project helps by demonstrating a technology, developing an agreed-upon research agenda, and enabling access to a unique facility to gain experience.

A Research Perspective on Carbon Sequestration[3]

Carbon sequestration options that rely on enhancing the natural cycle are essentially human interventions in the global carbon cycle. They depend upon a detailed understanding of fundamental processes to implement safe, effective, and verifiable sequestration options. This presentation emphasized ecological processes (Eds.).

[3] This plenary presentation of the Carbon Sequestration Workshop was made by Dr. Jerry Melillo of The Ecosystems Center of the Marine Biological Laboratory, Woods Hole, Massachusetts.

Verifiable measurement

Verification is the bottom-line issue for carbon sequestration. Verification is essential for acceptance of the carbon sequestration sinks, because credit for carbon sequestered is now an international business matter. It involves money, and documentation is necessary. But verification must be measurable, reproducible, and scientifically based.

There is widespread agreement that the largest anthropogenic carbon source is the gigatonnes of carbon from fossil fuel burning. Land-use changes, particularly in the tropics, add to that source term. The known sinks for that global carbon burden are accumulation in the atmosphere and accumulation in the oceans. Known sources exceed measured sinks. We can assume that the carbon missing from our accounting is being accumulated in the terrestrial biosphere.

If we want to store vast quantities of carbon in the terrestrial biosphere, the basic stoichiometry of natural systems must be obeyed. The laws of nature require that carbon be stored in particular ratios with other elements, including nitrogen. As the draft *Carbon Sequestration Research and Development* report points out, the most effective place to store much of this carbon is in the microbially resistant carbon or humus compounds of the soil. The stoichiometry of humus worldwide is fairly constant, and the carbon-to-nitrogen mass ratio is about 13 to 1. Therefore, in addition to managing carbon, we must manage the global nitrogen cycle. As discussed in Chapter 4 of this report, assessment is essential to understand the whole global ecological system and the way it will be affected by carbon sequestration.

Carbon sequestration—dynamics of the global carbon cycle

The dynamics of the global carbon cycle is a major research topic at many research centers. An experiment conducted by a group at Max Planck Institute in Germany and another group in Sweden attempts to understand the spatial component of carbon storage throughout the world in a geo-referenced perspective that examines “natural sequestration” as a consequence of atmospheric CO_2 fertilization, climate variability, and agricultural land use. The geo-referenced approach is particularly important because, if people are to buy into storing carbon, they will want to know where it will be stored and to be able to verify that it is stored there. The experiment uses a series of biogeochemical models for carbon, nitrogen, and water in terrestrial ecosystems that allow predictions about carbon storage or loss from terrestrial ecosystems over time. It produces estimates of carbon and nitrogen stocks and fluxes. Models of this sort require substantial geo-referenced data (e.g., location, cloudiness, elevation, atmospheric CO_2 content, nitrogen deposition, kind of vegetation, temperature, precipitation, and soil texture).

This model was run for the United States using increases in CO_2 observed over the 1980 time period, real climate as it changed over that period, and the changes in land use in the United States over that time period. The model suggested that in the United States during the 1980s, the annual carbon sequestration in terrestrial ecosystems was 136 teragrams. There has been a widespread CO_2 fertilization effect across the mainland of the United States. Will it continue forever? There may be a point at which additional CO_2 in the atmosphere will no longer act as a fertilizer; we may have saturated that effect. In addition, consider climate. Climate variability witnessed over the 1980s and early 1990s, in most parts of the United States, has actually promoted additional carbon storage. Now we can go to specific sites in the United States and test—validate the models and their predictive capability.

A little more carbon is stored through changes in land use. The model suggests that for the period 1900 to 1992, the United States was not a net sink for carbon but was actually releasing carbon largely as a result of land clearing in this country. Since the 1960s, the United States has been sequestering carbon, but in small amounts, not nearly as large as the Princeton group's estimate that North America is a 1.7-pentagram sink (Fan et al. 1998). The model indicates that the continent is a much smaller sink than that.

Digital environmental atlas

The draft *Carbon Sequestration Research and Development* report did not mention the need to organize extant information into accessible data sets that can be used by anyone. A digital environmental atlas is needed if we are to proceed with sequestration. Such an atlas is the analog of the human genome project: It is an information-based project that is essential for understanding and sustaining life on planet earth. We do not have to agree on model output, but at least we need agreement that we are all operating with the same concept (model) of planet Earth and that we use verified data inputs accessible to the scientific community. This digital environmental atlas should be updatable. It should be geo-referenced at some reasonable spatial scale that would require an international, government–NGO partnership. Currently, every group maintains its own environmental databases, resulting in much redundant effort and large disconnects. Remote sensing clearly would be tremendously helpful.

Integrated assessment models

There also is a need for integrated assessment models that take us beyond the ecological and the geological framework to consider the whole environmental system. We are beginning to couple economic systems, physical climate, chemical properties, and ecological attributes into an integrated formal modeling approach to explore scenarios and consequences. Integrated models of this sort could be tremendously helpful in evaluating concerns about the environment. They could interrelate climate change with other issues, such as biodiversity and land use, that are coupled to the carbon issue and climate change. An integrated assessment paradigm could allow us to place carbon sequestration in a larger context.

Environmental Community Perspectives on Carbon Sequestration[4]

The nongovernmental environmental community has divergent views of carbon sequestration. The following presentation illustrates how carbon credits could be used by conservation organizations to protect biodiversity (Eds.).

Environmental organizations have varying positions on carbon sequestration, and they do not all agree as to whether sequestration activities should be credited under the Kyoto Protocol. Major issues related to carbon sequestration include measurement and monitoring, effects on biodiversity, and the stability of the stored carbon. These issues all reflect concerns regarding impacts on environmental systems, and hence the advisability of the adoption of the Kyoto Protocol. Both the Environmental Defense Fund and The Nature Conservancy support the concept of carbon sequestration in forests and in land-use applications.

Skeptics of carbon credits are concerned that ambiguities in the protocols and in verification could result in "phantom credits" or "perverse" incentives that are harmful to the environment

[4] This plenary presentation was made jointly by Robert Bonnie of the Environmental Defense Fund and Michael Coda of The Nature Conservancy.

(i.e., cutting of old growth forests or conversion of grasslands). Another concern of some groups is that credits create a diversion from the real issue of emission reductions. On the other hand, advocates of credits see sequestration (“carbon credits”) as a positive means to address climate change that has enormous potential and that could garner a broadened political constituency. Underlying these arguments are fundamental scientific issues that affect policy options for carbon sequestration:

Durability. How does one credit carbon stored in a forest ecosystem, recognizing that each ecosystem has a life cycle and permanency exits only at a regional scale. If carbon sequestered in forests is credited, then the forest must be maintained (protected) indefinitely.

Leakage. Will augmentation of the natural carbon cycle result in carbon storage in reservoirs from which there is no leakage, or can leakage be measured? This issue becomes important when sequestration credits are applied to agricultural and managed forest ecosystems.

Additionality. Credits for carbon sequestration should be for storage beyond that which would occur naturally in the carbon cycle; false credits should not be given for uncertainties (missing sinks) in the global carbon budget.

The mission of The Nature Conservancy is “to preserve plants, animals and natural communities that represent the diversity of life on earth by protecting the lands and waters they need to survive.” It is the largest international organization dedicated to preserving biodiversity. The Conservancy views carbon sequestration credits as a powerful new tool to support its preservation of biological diversity in addition to enhancing carbon sequestration.

The Nature Conservancy supports several international forest sequestration projects, including the Rio Bravo Project in Belize and the Noel Kempff project in Bolivia. The Rio Bravo project is projected to offset 2.4 million tons of carbon over 40 years and is an approved project under the U.S. Initiative on Joint Implementation (USIJI). The land for this project is permanently dedicated under law for conservation. The Noel Kempff project, also a USIJI project, is projected to offset 15 million tons of carbon over 30 years. Other domestic and international forestry projects are funded by oil and utility companies.

Energy Industry Perspectives on Carbon Sequestration[5]

Increasingly, a broad spectrum of leaders in the energy and manufacturing industries are taking a proactive approach to controlling and reducing CO_2 emissions. The following presentation illustrates the approach being taken by Texaco (Eds.).

> *… Perhaps the dominant public policy issue for the energy industry as we enter the next century is the issue of global climate change. We share the concern of many about the impact of climate change on society and our business and we are going to play a positive role in contributing to the goal of managing and reducing greenhouse gas emissions. We believe our focus should be on ways to manage and reduce emissions and better protect the environment—not on choosing sides in the debate. We have nearly completed emissions baselining and we*

[5] This plenary presentation was made by Roland Borey, Manager of Environmental Strategies, Texaco Worldwide Exploration and Production.

are formulating a plan to manage emissions, which will be available by the end of the summer. We are also forecasting project emissions as we go forward with our business plans to enable us to better manage or reduce those emissions. We believe that the best way to show our commitment is to take action, not to debate the issue. (Peter Bijur, Chairman and CEO of Texaco, April 27, 1999.)

The chairman and chief executive officer of Texaco made this public commitment to reducing greenhouse gas emissions at the annual Texaco shareholders' meeting. Specifically, Texaco's commitments extend to the integration of greenhouse gas emissions management in all new projects. Further, as Texaco moves forward with its strategic planning for 2000 to 2004, it has committed to the integration of greenhouse gas emissions management into its strategic business thinking, as well, for all of its business units.

Operational and financial flexibility

At the White House Climate Change Task Force meeting in May 1999, Texaco expressed the following views.

- Industry needs the operational flexibility to pursue a portfolio of approaches to managing greenhouse gas emissions worldwide.
- Industry needs the financial flexibility to pursue the lowest-cost approaches wherever possible, including such approaches as forestry management and conservation.
- The United States and other nations should negotiate for rules that will allow the broadest set of approaches that can offset emissions and that are creditable.

Texaco supports the carbon sequestration road mapping effort that will lead to broadening the scope of the operational flexibility and financial flexibility that industry will need to manage greenhouse gas emissions.

Integrating emissions management with business planning

The essence of Texaco's efforts to integrate greenhouse gas emissions management with business planning is indicated in Fig. 9.1. It shows a generic emissions projection graph and some approaches that a typical Texaco business unit may consider in its management or reduction of greenhouse gas emissions.

The essence of Texaco's greenhouse gas emissions management in our business planning is the following:

- Project emissions growth
- Know the gaps between emissions growth and the ability to reduce or offset
- Plan for different levels of reduction and offset

Texaco does this for both strategic planning and new project planning processes.

For new projects, Texaco has taken a proactive approach to consider a list of ways to reduce emissions at the proposed facility and a list of ways to offset emissions outside the facility. It is committed to evaluating the feasibility, the costs, and the benefits of these approaches and incorporating them into a greenhouse gas emissions management plan.

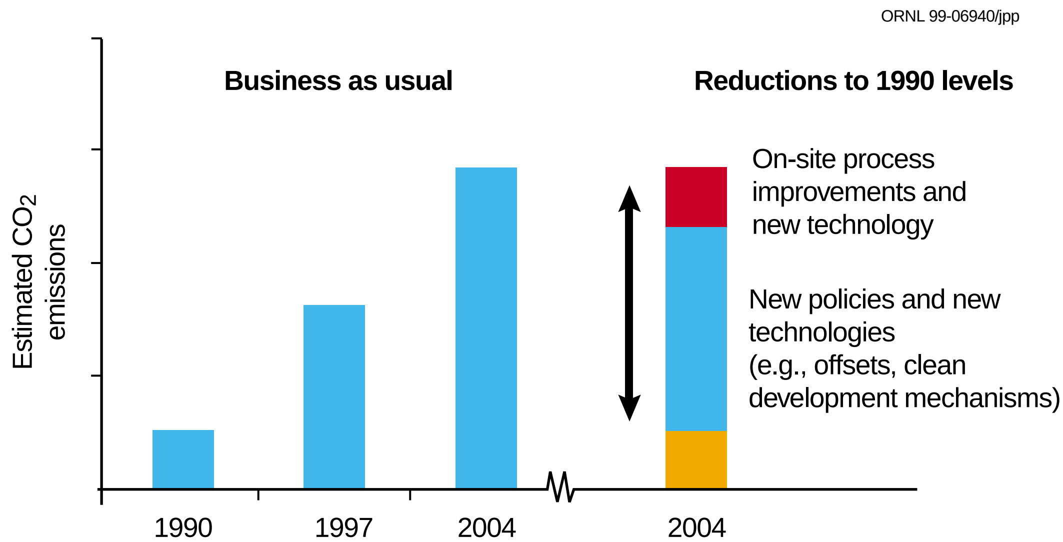

Fig. 9-1. Emissions projection graph, and approaches a Texaco businesss unit may consider in managing greenhouse gas emissions.

For example, as a co-venturer in the Gorgon Liquefied Natural Gas Project in Western Australia, Texaco supports the voluntary agreement that was signed with the Australian Greenhouse Office, the leading Commonwealth authority on greenhouse matters. Signed in December 1998 by the Gorgon Project, the agreement contains a detailed greenhouse gas emissions management plan that incorporates a list of continuous design improvements that would result in reducing greenhouse gas emissions by 1.7 million tonnes from a previous baseline design. The project is committed to further design improvements, as well as the evaluation of approaches to offset emissions outside the proposed facility.

The need for research: long term and short term

The need for carbon sequestration is clear, given the ambitious emissions reduction targets adopted in the Kyoto Protocol. Before industry can use some of these sequestration approaches, Texaco offers DOE and the participants at the workshop the following recommendations to guide R&D. The directions and criteria for long-term research need to consider

Technical feasibility: What amount of carbon can be sequestered at a time? Will it stay sequestered? How long will it stay sequestered? Most important, will the sequestration activity fit with an industry's operations? For example, the oil and gas industry has extensive experience with down-hole technologies and with offshore developments. These will be a natural fit with geologic sequestration.

Environmental effects: What are the side effects of a particular method, if any, on the ecosystem? Are there any safety concerns?

Cost-effectiveness: For the amount of carbon sequestered, what is the cost-effectiveness of the technology?

There is a strong need for shorter-term research as well—such as monitoring that would allow sequestration activities to be credible and creditable. For example, significant development work will be needed on monitoring and verification for geologic sequestration. Industry must have cost-effective monitoring. At a minimum, short-term research must focus immediately on establishing the technical and procedural framework to rank the amount of credible sequestration over specific periods of time.

Texaco has made a public commitment to integrate greenhouse gas management with its business planning processes. At the same time, the need for operational and financial flexibility is clear under the ambitious emissions reduction targets of the Kyoto Protocol. Texaco urges the United States and other parties to negotiate for rules that would allow for the broadest set of credible and creditable emissions reduction approaches, as well as emissions offset approaches. Further, there is a clear need for carbon sequestration and the R&D needed to make these approaches feasible, cost-effective, and environmentally sound. Texaco supports DOE's effort in guiding and funding the R&D approaches necessary to satisfy these needs.

REPORTS FROM WORKSHOP BREAKOUT SESSIONS

Participants in the Stakeholders Workshop met in breakout sessions organized around the technology areas considered in this report: separation and capture; ocean, terrestrial, and geologic sequestration; and advanced biological and chemical processes (combined into advanced concepts). A rapporteur captured the main points of the discussion in each breakout session, and these summaries follow.

Carbon Separation and Capture[6]

Carbon dioxide is generated by numerous anthropogenic activities. The draft *Carbon Sequestration Research and Development* report identifies the major sources. Additional sources could be considered either subsets of the ones already included or additional minor sources. Table 9.1 shows sources identified in the previous draft of the report and additional sources identified in the breakout session. The combined list likely is not complete, but it represents a high fraction of the sources of anthropogenic CO_2 emissions.

Many CO_2 separation technologies currently exist and are being used commercially. They have been optimized for specific industrial applications, including CO_2 removal from syngas (mixtures of hydrogen, carbon monoxide, CO_2, and methane), natural gas, and landfill gas. These separations are generally made at pressure with relatively high CO_2 concentrations, characteristics that tend to make separation easier. Some of these technologies have even been applied to removing CO_2 from combustion flue gases, a process found to be much more expensive. This experience base suggests that a major issue for carbon sequestration is the cost (both capital and operating) of CO_2 separation and capture.

There is value in summarizing existing technologies and costs with
- all assumptions and calculations used being consistent
- costs developed only for combinations of technologies and sources of CO_2 that are amenable to each other
- reported costs including life-cycle costs, amortized capital costs, and energy consumption costs

[6] The rapporteurs for the separation and capture breakout group at the Stakeholders Workshop were Joe Abrardo of Air Products and Chemicals and Lorie Langley of ORNL.

Such an effort could result in a compilation similar to that in Table 9.2 (the blanks would be filled in as information becomes available) and could be used as the basis for future research. Improvement and re-optimization of these technologies will lower costs; but, in reality, a significant step change in cost, rather than incremental improvement, is needed. Future R&D should be focused on this fact.

R&D priorities

Many factors will determine the selection of a particular technology for the separation and capture of CO_2 and the prioritization of the R&D related to it. The process is complicated by several issues, including these:

- Several types of streams containing CO_2 must be addressed (Table 9.1). Each type of source has a different operating pressure and temperature, CO_2 concentration, and scale. These critical parameters determine the appropriateness of the technology for the particular application. In addition, sources of the CO_2-containing streams may change as new technologies are commercialized (e.g., natural gas combined-cycle gas turbines, Vision 21).

Table 9.1. Sources of anthropogenic CO_2 emissions

Previously identified sources	Additional sources
Fossil-fuel-based power generation	Industrial heat generation
Natural gas production and upgrading	Associated gas
Hydrogen production	Hydrogen production in fertilizer plants
Oil refineries	Petrochemical plants
Iron and steel plants	Other metals plants
Cement and lime production	
Residential heating	
Transportation	
	Waste incineration
	Landfill gas
	Coal bed/coal mine methane
	Heavy manufacturing

Table 9.2. Example of proposed reporting of CO_2 separation and capture costs ($/ton)

Application	Absorption	Adsorption	Low-temp distillation	Membranes
Power generation (coal)				
Gas turbines (natural gas)				
Natural gas upgrading				
Hydrogen production				
Landfill gas recovery				
etc.				

EXAMPLE

- The sequestration requirements (e.g., CO_2 purity, pressure, and, possibly, physical state) imposed on the separation system are not well defined yet and may vary depending on the sequestration route selected.

- Energy consumption and capital costs for the separation system may be sensitive to the desired, but as yet undefined, CO_2 recovery level. Determining goals for this parameter (it may be different for each technology) is critical to the overall cost optimization and magnitude of CO_2 emission reduction.

- Other initiatives may significantly affect characteristics of the CO_2 stream required by the separation system (e.g., fuel decarbonization, which moves the CO_2 separation from post-combustion to pre-combustion, and new oxygen-based combustion routes).

- Emission credits or allowances.

These facts and uncertainties suggest that no single separation and capture technology will satisfy all the requirements, and a broad portfolio of technologies is required. Thus any R&D program needs to focus on developing a broad portfolio rather than a specific technology.

R&D prioritization should balance impact on CO_2 emissions with the complexity of the separation. The R&D programs should balance (1) more immediate applications that are less complex and more amenable to current technologies but that have less impact on emissions and (2) more complex but larger-impact opportunities. Confirmation from the near-term applications can provide valuable input to the longer-term ones.

A methodology for displaying the magnitude and the complexity relationships of various sources of CO_2 emissions is shown in Fig. 9.2. This example is qualitative and incomplete, but it presents important concepts. Such a framework could help prioritize the R&D program. Incentives for any actual projects are unclear, especially considering that there are no current legislative mandates in the United States. There is no overall strategy guiding the demonstration projects that are under way (mostly outside the United States). A framework sponsored by DOE would help to focus future U.S. R&D efforts. Criteria should include both

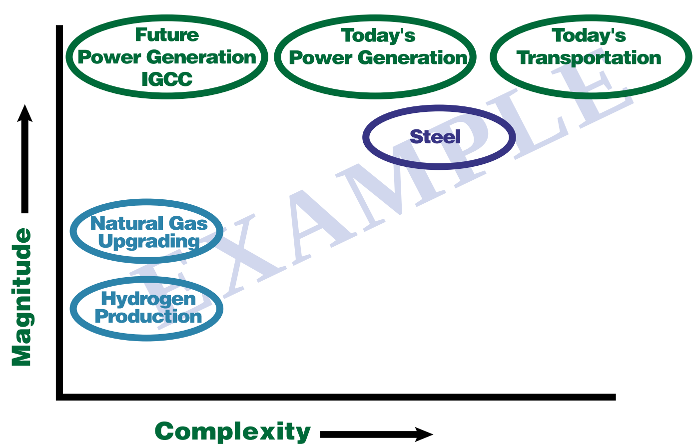

Fig. 9.2. Example of methodology of displaying prioritization issues.

business and economic aspects of the program. Completion of the background material discussed in this breakout session would provide an essential foundation to the program.

Specific recommendations

- Care should be taken to focus research on reasonable combinations of sources and separation technologies.
- Short-term, incremental improvements that can be demonstrated quickly and provide valuable early feedback to the overall program should be pursued. However, effort must also focus on longer-term, order-of-magnitude changes in cost.
- Real applications that have the potential for a material contribution to CO_2 capture, and are of interest to an industry partner, should be identified and supported. DOE should provide economic support during all phases (R&D, demonstration, and implementation) of a program.
- DOE needs to engage industry, both technology users and equipment suppliers, more than is done today.

Carbon Sequestration in the Oceans[7]

The agenda for the discussion of carbon sequestration in oceans covered four topics: research priorities for direct injection, research priorities for enhancement (e.g., fertilization), linkages and partnerships, and a timeline for developing technologies.

Research priorities for direct injection

The starting point for setting research priorities for direct injection and enhancement was the draft report *Carbon Sequestration Research and Development* (DOE 1999).

Participants expressed five different viewpoints regarding the costs of ocean sequestration of carbon.

- Direct injection ocean carbon sequestration is likely to be expensive. Not only the cost of transporting the CO_2 from its source to the deep ocean, but also the cost of separation and capture, probably the largest component of the cost, must be considered.

- It is difficult to judge the future cost-effectiveness of this option. The value of sequestering carbon could increase dramatically, changing the context, and it is difficult to predict how technology will improve.

- Cost-effectiveness needs to be evaluated as part of the larger system. For example, we need to compare carbon sequestration with alternative approaches to carbon mitigation.

- Financial benefits that could occur as a by-product of ocean carbon sequestration (e.g., fish farming or mariculture) could reduce costs.

- Currently, questions about technical and environmental feasibility are more important than questions about costs.

[7] Rapporteur for the ocean sequestration breakout group at the Stakeholders Workshop was Howard Herzog, Massachusetts Institute of Technology.

Two topics that could influence the effectiveness of ocean carbon sequestration need further research: (1) the effect of singular events, such as hurricanes or deep-water seismic events, and (2) the effect of feedback from climate change on ocean circulation.

A representative of the environmental community voiced several concerns:

- Natural oceanic processes currently sequester about 2 GtC per year because of increased CO_2 concentrations in the atmosphere. Some argue that the environmental impacts of purposeful carbon sequestration in the oceans should be compared with the impacts of “excess” natural carbon sequestration already taking place. Instead, the baseline with which purposeful sequestration should be compared is one with no excess atmospheric CO_2 concentrations and no excess natural oceanic carbon sequestration. The latter situation would be achieved through a combination of energy policies.

- Carbon sequestration needs to be compared with other approaches (e.g., renewable energy sources).

- Even though ocean carbon sequestration would reduce atmospheric concentrations of CO_2, extra energy is required to capture, transport, and sequester the CO_2. This extra energy expenditure should be taken into account. For instance, over the centuries, even the deep ocean will equilibrate with the atmosphere, and the extra CO_2 produced from the energy used sequestering the CO_2 will end up in the atmosphere as well as in the ocean.

Despite the variety of views in the session, there was a reasonable consensus on understanding environmental impacts as the top research priority for direct injection. Some of the specific suggestions were

- Generate more details on the effects of pH and CO_2 on marine organisms.

- Look for opportunities to “piggy-back” biological experiments on planned field experiments, such as the ocean storage project in Hawaii (Adams et al. 1998). (Additional information on this planned experiment can be found at www.CO2experiment.org.)

- Investigate natural analogs of ocean injection, such as deep-water CO_2 vents.

- Increase understanding of how to use hydrate formation to mitigate environmental impacts (e.g., to isolate CO_2 from or dilute CO_2 into the water column).

- Use the IRONEX template in conducting field work. This means opening up a project to multiple competitive proposals and choosing the best ones.

- Consider setting up an experimental facility to carry out long-term experiments.

Research priorities for enhancement

The discussion on enhancement focused on the iron fertilization technique. There were several suggestions for additions, clarifications, and revisions to the draft report *Carbon Sequestration Research and Development.*

- Both continuous and pulsed experiments are important. The type of experiment influences the export efficiency.

- Concerning the impact on sea-air fluxes (climate feedbacks), the report may overemphasize the role of CH_4; N_2O and dimethylsulfide also should be considered.
- In addition to the compounds mentioned in the report that are important to the biogeochemical cycle (carbon, nitrogen, phosphorus, silicon, and sulfur), important elements include cobalt, zinc, and perhaps selenium.
- The oceans should be included in the digital environmental atlas (of baseline data) that was discussed in the plenary presentation by Dr. Jerry Melillo.
- Cost and energy requirements need analysis.
- To understand the entire system, there is a need for multi-parameter experiments coupled to a model.

Three priorities were identified:

- Increasing understanding of the export efficiency from the ocean surface to the deep ocean is the key to understanding the effectiveness of the iron fertilization process.
- An experiment should be conducted at large enough scales (spatial and temporal) to increase understanding of the fertilization process.
- Developing technologies and methodologies for measurement and verification, including modeling tools, is essential.

Linkages and partnerships

There are two key linkages to ocean sequestration. First, the fate of ocean injection necessarily will be tied to the costs of separation and capture. Second, ocean injection is particularly closely linked to the international community. Ocean injection is especially important to other countries for many reasons, including (1) the geography of such countries as Japan with greater proximity to the ocean than to underground reservoirs and (2) the international nature of the oceans. Other suggestions included these:

- Coordinate with carbon cycle research. There is an ongoing program on U.S. Carbon Cycle Science that includes DOE, the NSF, NASA, and the USGS.
- Include technology being developed for offshore oil and gas production.
- Carry out a large-scale, long-term IRONEX experiment, as recommended by the Decadal Planning Document of the NSF's biological oceanography group.
- Use the DOE Ocean Carbon Sequestration Center to coordinate/collaborate with other organizations, including other government agencies.
- Explore links to terrestrial sequestration. For example, there may be a change in transport of dissolved organic carbon from land to the ocean in response to terrestrial sequestration strategies.
- Investigate industry participation. This must be a two-way street: industries will be most interested in participating in those projects that offer prospects of financial gain.

R&D timeline
To acquire the knowledge to implement direct injection and/or enhancement ocean carbon sequestration by 2025, we must accomplish the following things:

- In the short term, pursue activities to build a foundation for long-term, large-scale experiments:
  - — Hold planning/expert workshops
  - — Conduct laboratory studies
  - — Perform theoretical studies/modeling
  - — Carry out pilot/feasibility studies
  - — Develop basic tools (e.g., monitoring)
  - — Build up links with other agencies, industry, and international organizations
  - — Conduct public outreach

- In the mid-term (2005–2015), conduct these long-term, large-scale experiments with modeling and monitoring components and a primary focus on environmental impacts.

The ocean sequestration session was chaired by Ken Caldeira of Lawrence Livermore National Laboratory and Jim Bishop of Lawrence Berkeley National Laboratory, who are the co-directors of the DOE Center for Research on Ocean Carbon Sequestration. Twenty-eight people attended the breakout session: six from DOE, nine from the national laboratories, two from other government agencies, four from academia, two from environmental groups, and five from the private sector.

Carbon Sequestration in Terrestrial Ecosystems[8]

There already is a significant body of information on productivity and carbon cycling in agricultural ecosystems (crops and soils) and above-ground biomass production in managed forests. R&D breakthroughs in the following areas are critical:

- the understanding of fundamental biogeochemical mechanisms that control the partitioning of carbon among plant cellular components and above- and below-ground components, and the allocation of carbon among long- and short-term pools in soils
- the ability to measure and verify net ecosystem exchange (NEE), above-ground biomass, and soil carbon,
- landscape, regional, and global assessments of carbon stocks
- the use of process-level understanding for integrated assessments and for guiding land-use management

It seems likely that focused R&D could, within 25 years, result in new knowledge and technology for terrestrial systems that would make a significant contribution to the larger vision of carbon sequestration.

Sequestration in terrestrial ecosystems is connected to other carbon sequestration approaches and aquatic and marine ecosystems. For example, nutrient and organic matter transport to the ocean margins is an important connection that could be affected by changes in terrestrial ecosystems. Partnerships and collaborations among public and private research communities and stakeholders and across federal funding agencies are critically important.

[8] The rapporteur for the terrestrial sequestration breakout group at the Stakeholders Workshop was F. Blaine Metting, Pacific Northwest National Laboratory.

Systems

In the draft *Carbon Sequestration Research and Development* report, terrestrial ecosystems are categorized as high-, medium-, and low-intensity management. However, the participants reminded DOE that the categories are fluid and overlapping. Depending on a given approach to enhancing carbon sequestration in a given ecosystem, the ecosystem could be in two or all three of the categories. These additional issues were raised:

- The single-minded emphasis on increasing carbon sequestration should be modified. Optimizing, rather than increasing, would imply that the objective should include enhancing carbon sequestration, but with due concern for potential negative environmental impacts to ecosystems. We cannot predict the consequences of some actions, and it is important to consider approaches to limit the loss of carbon from ecosystems, as well as approaches to add carbon.
- The distinction between “natural” and “managed” ecosystems should be more clearly or explicitly defined.
- Greater emphasis should be placed on restoring carbon lost from ecosystems as a consequence of past land use and on restoration of some types of ecosystem types (i.e., wetlands and riparian zones).
- A two-dimensional matrix of “net increase” plotted against “management intensity” could help to conceptualize and categorize land-use management options for different ecosystems. A given ecosystem could thus be represented more than once.

Objectives and strategies

In the draft *Carbon Sequestration Research and Development* report, the objectives discussed for “increasing” terrestrial carbon sequestration are (1) increase below-ground carbon, (2) increase above-ground carbon, and (3) optimize land area (per an equation component in the road map). These may not be the best categories from the perspective of whole-ecosystem approaches, and some recommendations for establishing integrated objectives were offered:

- Identify overarching objectives. Regional NEE should be optimized and existing carbon stocks protected.
- Emphasize “whole ecosystems” and consider them in the context of landscapes. In particular, work toward improving understanding of below-ground carbon stocks and fluxes across ecosystems.
- Consider relationships among NEE, net primary production, and carbon sequestration. There is a great need to understand relationships between NEE and carbon longevity and to identify the controlling processes.
- Enhance emphasis on ancillary benefits and unintended consequences of actions aimed at managing carbon sequestration in terrestrial ecosystems.
- Acknowledge more clearly the links to other road map components [e.g., oceans (dissolved organic carbon movement)].
- Reemphasize the importance of conceptualizing strategies in the context of whole ecosystems and ecosystem dynamics. Regardless of the strategy, it is ecosystems that are managed and that therefore must be understood.
- Acknowledge biogeochemical cycles and their interdependencies at the strategy level.
- Conduct assessments of terrestrial carbon sequestration potential and achievable potential at the regional and national scales.

R&D needs

The R&D needs articulated in the draft *Carbon Sequestration Research and Development* report are largely inclusive and generally represent high priorities for R&D. The R&D objectives deemed to be high priorities for investment can be considered in the categories of understanding, measurement, assessment, and implementation.

Understanding environmental processes

- Understanding of terrestrial carbon sequestration processes must come first, then implementation. Optimization requires understanding.
- Understanding of fundamental mechanisms controlling carbon sequestration in and loss from terrestrial ecosystems is required to address issues such as increasing recalcitrant carbon, particularly in soils, and controlling the soil carbon active fraction.
- Emphasis is needed on microbial communities and fundamental carbon sequestration processes.
- Improved understanding is needed of spatial and temporal dynamics of carbon cycling as related to sequestration and loss. In agro-ecosystems, "We (partially) know it, but we don't *understand* it."
- Understanding of heterogeneity should be addressed at all scales.
- The need to understand linkages and impacts of carbon sequestration process modifications on other cycles should be addressed (i.e., nutrient cycles, the hydrologic cycle—particularly at higher spatial resolution/scales).
- An understanding of current controls over NEE and carbon sequestration/longevity among ecosystems is needed.
- Process models that both feed ecosystem research models and support assessment activities are needed.

Measurement and verification of carbon storage

- Measurement needs for carbon sequestration in terrestrial ecosystems are of two kinds, which are different but with some overlap: scientific needs versus verification requirements.
- The ability to measure (and verify with ground-truthing) NEE to within 5% within ecosystems is a potential target.
- Improvements in measurement approaches and technology for above-ground biomass are needed beyond agricultural ecosystems.
- Technology for improved measurement of soil carbon is a critical requirement. The ability to measure small changes over relevant (years to decades) time scales is needed, as is the need to be able to measure and interpret spatial-temporal variability.
- Measurement technologies should address the following issues: minimal invasiveness, rapidity, sensitivity, reproducibility, vertical precision, cost, and better models for purposes of verification.

Assessment and evaluation of sequestration

- Assessments are needed for two distinct purposes: (1) to refine scientific direction and inform the scientific community and (2) to inform decision makers and public constituencies.
- A digital environmental atlas is a critical need. Group members representing the USGS, NASA, and USDA favor a cross-agency effort with DOE.
- Baseline inventories of potential and achievable potential are needed.
- Integrated assessments are needed, including (1) life-cycle costs and whole-carbon accounting for proposed sequestration approaches, (2) impacts of carbon sequestra-

tion approaches on biodiversity and fluxes of other greenhouse gases, and (3) human environmental health.
- Socioeconomic impacts must be assessed.
- Stakeholder and public constituency groups should have easy access to data.

Implementation

- It is important to link process-level understanding with integrated assessments and guidelines for management options.
- The potential benefits and other consequences of land use management strategies that improve carbon sequestration should be communicated.
- More emphasis is needed on restoration of lost ecosystems (e.g., wetlands) and of carbon lost from manipulated ecosystems (i.e., agriculture).
- Analysis is needed of incentives for implementation.
- Links to social and economic systems must be addressed.

Partnership opportunities

- A digital environmental atlas is an opportunity for cross-agency collaboration
- Field research at various types of sites: USDA/university network of long-term agricultural sites, NSF long-term ecological research sites, DOE's National Environmental Park network, USGS sites, Forest Service lands
- A dedicated carbon sequestration test facility for further conceptualization and development
- Industry sites: the Canadian GEMCO program with dry land farmers, industry, forest sites

The terrestrial sequestration session was chaired by Gary Jacobs of Oak Ridge National Laboratory, co-director with Blaine Metting of Pacific Northwest National Laboratory of the DOE Center for Research on Enhancing Carbon Sequestration in Terrestrial Ecosystems. The breakout group comprised about 45 individuals, of whom more than 30 participated for most or all of the breakout session. The group included representatives of DOE, the DOE national laboratories, The U.S. Department of Agriculture's Agricultural Research Service and Forest Service, EPA, NASA, the states, the American Society for Mechanical Engineering, The Nature Conservancy, the university community, and the private sector.

Carbon Sequestration in Geologic Formations[9]

Fundamental research is needed in multiphase flow in porous media, including reaction path modeling, and methods are needed to monitor the performance and safety of CO_2 injection into geologic environments.

Comments on carbon sequestration R&D strategy

- Implementation of sequestration will be driven by economics. No company will competitively disadvantage itself by sequestering CO_2 with no financial return.
- Control of a CO_2 source and a CO_2 sequestration site will rarely reside with the same legal entity. There will be significant issues of landowner and royalty owner rights and financial needs in most geological sequestration activities.
- DOE should form a program steering committee with representation from industry, environmental action groups, and appropriate government agencies.

[9] The rapporteurs for the geological sequestration breakout group were David Thomas, BP Amoco, and Robert Burruss, U.S. Geological Survey.

- Most of the suggested projects are interrelated. They may begin at a small scale and grow.
- Priorities should be reordered within the short- to long-term priority continuum.
  - — Monitoring studies should begin early and continue through the long term. Baseline definition and monitoring techniques will be broadly applicable and needed in each of the target sink types.
  - — Engineering-related topics as applied to full-scale plants should take place relatively late. Pilot projects should begin early and progress logically to full-scale plants as dictated by success and need.
- Proposed projects should be evaluated for their fit with the time scale and planned into the appropriate time and sequence.
- There is a natural interrelationship between projects that was not clear in the geologic sequestration chapter in the draft report *Carbon Sequestration Research and Development.*
  - — Brines exist in all reservoirs and should be studied as a system rather than as applied to a particular reservoir type.
  - — A relatively limited range of minerals make up the reservoirs and are common to all. The program should address them as a system rather than as associated with particular reservoir types.

Issues

Monitoring
- Detection of CO_2 movement
- Validation of storage
- Joint inversion (geophysical and geochemical)
- Tracers of reaction progress and CO_2 leakage
- Long-term performance assessment

Brines
- Most important and most challenging reservoir
- Reactivity and impact on storage capacity
- Enhancement of solubility and mineral trapping

Field tests, pilot projects

Improved monitoring methods

Coupled monitoring and modeling
- Comparison of system properties
- Opportunities for fundamental research

New topics
- Microbial conversion to useful products (CH_4)
- Hydrates (trap CO_2, release CH_4)

Environmental concerns
- Unintended consequences, for example, mobilization of metals
- Gaining public confidence

Multiphase flow

Communication/education

Gaps in knowledge and ideas
- Efficiency of filling porosity in multiphase flow
- Economics of CO_2-enhanced oil recovery in oil reservoirs
- Rock/CO_2/oil/water interactions
- Geomechanical response to changing pressure

Monitoring
- Safety
- Performance assessment
- Process research
- Project-specific requirements
- Scale of measurement (field, well, surface)
- Baselines

Coal
- Performance assessment
- Formation characterization
- Storage capacity/unit volume or mass

Brine formations
- Performance assessment (critical)
- Rates of reaction and dissolution
- Public reaction/perception

The division of geologic sequestration research topics as shown in Tables 5.2 through 5.4 in the draft *Carbon Sequestration Research and Development* report does not indicate how programs support system objectives. A different program management structure is suggested that takes advantage of the strengths of DOE and addresses the primary issues in a structured way. The suggested program management structure in Table 9.3 will minimize overlap and maximize synergism while highlighting the connectedness of the activities. The topics included are examples of the kinds of activities that should occur in each time frame.

Setting priorities

Geological processes. Cross-cutting technologies identified in the draft *Carbon Sequestration Research and Development* report should be given priority as shown in Table 9.4.

Reservoir systems. Priorities differ according to objectives. If the objective is implementation of sequestration, the priorities will be based on minimizing cost, materiality (size of target), time frame, and revenue streams from enhanced oil recovery or tax credits. From this perspective of implementation, the priorities are

1. Oil reservoirs—highest potential for a revenue stream from enhanced oil recovery
2. Coal reservoirs—gas streams are a strong revenue stream
3. Gas reservoirs—less knowledge about “flooding” a gas reservoir with CO_2 is available
4. Brine reservoirs—these are purely disposal targets with no revenue presently available

If the objective is research to understand the sink targets, the order is nearly reversed. Brine reservoirs are the least understood, and oil reservoirs the best understood. Using this criterion, the priorities are

1. Brine reservoirs—broad research needs in brine chemistry, geology of sealing mechanisms, and flow characteristics
2. Coal reservoirs—broad research needs in coal types, adsorption-desorption phenomena, coal body sealing mechanisms
3. Gas reservoirs—major research need for understanding of flow interaction (flooding) of nearly depleted gas reserves with high concentrations of CO_2
4. Oil reservoirs—most well known, but research needed on targeting sequestration rather than conventional reservoir engineering

Table 9.3. Suggested program structure for geological sequestration

Topic	Short <2005	Medium 2005-2010	Long >2010
Fundamental science: Studies on chemistry and processes. Reservoir model, flow in porous media, thermodynamics	Brine/CO_2--- Oil/CO_2---- CO_2 f(P,T,X) Modeling----	--------------> --------------> --------------> -------------->	--------------> --------------> --------------> -------------->
Monitoring: Techniques for establishing baselines and for monitoring during and after injection	Surface and subsurface techniques	Monitoring programs during operation	Monitoring for long-term assurance of safety
Screening: Tools to choose target reservoirs and sites. Geological, engineering, political, safety	Oil and gas Coals	Coals, brines	Brines
Engineering: Studies to provide technology assessment, cost/benefit analysis by consistent techniques. Pilot-scale to full-scale designs	Technology assessment. Cost/benefit analysis. Pilot-scale plants and designs	Demonstration scale plants. Full-scale designs	Full-scale plants

Table 9.4. Priority of cross-cutting technologies

Multiphase reactive, multi-component, active transport phenomena:	High priority
Phase behavior of mixed fluids. Physical and chemical interactions:	High priority
CO_2 dissolution of formation materials and studies of reaction kinetics and thermodynamics:	High priority
Coupled H-M-C-T processes and modeling:	High priority
Microseismic mechanisms and deformation modeling:	Lower priority
High resolution geophysical modeling:	Lower priority

Implementation of CO_2 sequestration will be driven by economics. Within the United States, there are at present no financial incentives to sequester CO_2 except incidentally as part of an enhanced oil recovery project. Oil and gas reservoirs will be the first set of targets, for the reasons outlined in the priority setting exercise.

Commercial-size projects will be very expensive and dominated by the costs of the following items:
- separation of CO_2 from process streams
- transportation to the sink target
- compression to injection pressures

A program's life should be similar to this progression:
- Project identification
- Sensitivity analysis
- Technology assessment
- Laboratory studies
- Pilot studies with extensive monitoring
- Demonstration scale studies with targeted monitoring and with parallel development of changes dictated by early pilot and demonstration activities

Advanced Concepts for Carbon Sequestration[10]

Two principles should shape both the prioritization of concepts and their evaluation in selecting candidates for further development:

- Funding for novel biological or chemical approaches to carbon sequestration should be provided without undue prescriptions or limitations. It is impossible to predict what form successful novel processes might take in addressing carbon sequestration. Opportunity is needed for high-impact, "out-of-the-box" thinking.

- Risk, cost, and development time should be addressed in project proposals.

Based on these ground rules, four key objectives were identified:

- Develop breakthrough processes with the potential to sequester large amounts of CO_2 and other greenhouse gases with sequestration lifetimes of greater than 100 years.

- Create new tools, concepts, and information that expand our ability to develop sequestration options and understand their impacts on environmental systems.

- Develop key subprocesses that enhance other sequestration options (i.e., geological, terrestrial, oceans). An example is condensing gaseous CO_2 into water-soluble acetates or solid forms of carbon to reduce containment volumes or increase capacities of geological repositories.

- Develop value-added products from greenhouse gases, as opposed to disposing of them in a relatively inert and unusable form. CO_2 can be used as a feedstock for useful products.

[10] The breakout groups for Advanced Biological Processes (Chapter 6) and Advanced Chemical Concepts (Chapter 7) were combined at the Stakeholders Workshop into an advanced concepts group. James Ekmann, DOE Fossil Energy Technology Center, was the rapporteur for this group.

R&D priorities focus on two primary and numerous secondary criteria. The first priority is to identify approaches capable of consuming large amounts of CO_2 and sequestering it for long times. The second priority is to develop by-products that are well characterized in terms of future chemical changes, toxicity (including that of potential derivatives), and dispersal into the environment. Other secondary priorities include these:

- Focus on 2030 and take advantage of opportunities that occur before then.
- Consider CO_2 a resource for use in products as well as a waste to be disposed of.
- Address serious potential problems in the other sequestration areas, for example, controlling reactions between injected CO_2 and the cap rock that might limit geologic reservoir capacity.
- Continue road-mapping activities by looking first at the desired end result (that is, the sorts of products desired) then looking back toward the process developments needed to produce the desired end-state. This process offers a means to develop revolutionary rather than incremental processes.
- Maintain a diverse portfolio of R&D aimed at breakthrough technologies, since high-risk approaches suggest that some of the options to be explored will fail to meet cost and performance criteria.
- Support development of processes that offer potential multiple (integrated) benefits—sequestration being only one of them—but no single benefit that satisfies simple cost and performance criteria. Means are needed to develop assessment techniques that optimize multiple benefits including those not funded currently (see next bulleted item).
- Develop life-cycle analysis for total carbon emissions and energy requirements to provide a coarse filter to measure net CO_2 emissions for proposed options. This filter might identify additional issues to be evaluated to decide if further work is merited. Such methods should be used before innovative approaches are subjected to economic evaluations that might be driven by the uncertainties.
- Develop new tools, processes, and information to expand the range of sequestration options and facilitate our understanding of impacts of these emerging technologies.

The following are examples of advanced biological and chemical processes for which R&D is needed. (The list is not prioritized.) Many of the concepts are discussed earlier in this report.

Advanced chemical concepts

- Produce durable goods, products and infrastructure from CO_2. This process links the demand for high-volume products (tens to hundreds of megatons of product consumed per year), such as those used in infrastructure and other commodities, to population growth. Potential products include artificial soils, lumber for buildings, roadbeds, plastics and composites, and bio-based materials. Added benefits from this approach may include, for example, replacing heavier steel automobile components with lighter-weight plastic or composite materials. Downstream exhaust emissions are lower for lighter vehicles, and upstream emissions are reduced because less steel manufacturing is required.

- Use materials that contain carbonate magnesium to form magnesium carbonates. This approach currently focuses on mining olivine and serpentine ores and reacting them with CO_2 at elevated temperatures and pressures to produce $MgCO_3$, which can be stored indefinitely or used. The process can potentially be used in above-ground, closed-loop processes or in-situ.

- Use supercritical CO_2 to form man-made geothermal hot-rock reservoirs and as a heat-transfer fluid in geothermal power plants. Supercritical CO_2 is somewhat superior to water as a heat transfer fluid and does not mobilize heavy metals contained in the subsurface environment.

- Produce ammonium bicarbonate (NH_4HCO_3) fertilizer from water, ammonia, and CO_2. The fertilizer will dissociate in the near-surface soil; the ammonia will act as a plant/crop fertilizer, and the bicarbonate ion (HCO_3) will migrate into the deep soil and ultimately into subsurface water. Carbonate lifetime, soil counter ions, transport of the bicarbonate ions to the aquifer, and reactions in the aquifer must be considered.

Advanced biological concepts

- Increase plant enzyme activity. For both carbon (rubisco, PEP carboxylase) and nitrogen fixation (nitrogenase) pathways, research may increase plant enzyme activity and increase biomass yields. A related approach is pathway engineering to produce carbon-containing metabolites (intermediates) that can be sequestered or used in some way.

- The research programs on ocean fertilization should also consider the near-shore environment (Wilde et al. 1990).

- Use biological processes to produce a compact, easily stored form of CO_2. Use microbial processes to produce water- or petroleum-soluble compounds (i.e., acetate) that can be stored indefinitely in smaller volumes than other forms of CO_2 intended for geologic sequestration.

- Modify plants to produce durable materials. Lignin-derived materials already play a significant role in improving the performance of a variety of materials, including concrete, adhesives, fertilizers, and road surfaces. (Lignin Institute 1999). Research to alter the composition of plants has the potential to increase the yields and ease the recovery of useful plant products, as well as increase the stability of materials derived from them. The potential for this approach to increase the amount of carbon tied up in products is unclear and would need to be evaluated. Increased use of lignin is under investigation.

Impacts on other R&D efforts

Research in advanced chemical and biological concepts could be useful in other sequestration processes. There is potential for large impacts in terrestrial carbon sequestration approaches through the use of CO_2-derived artificial soils for reclamation of degraded land, as well as improvements in plant photosynthesis that would benefit biomass production and stress tolerance. Improving ocean and soil algal and microbial processes to enhance carbon capture and retention holds the potential for significant increases in the amount of carbon that could be sequestered. Volume reduction in liquid and solid CO_2-derived products may improve geologic sequestration.

According to an industry representative at the session, innovative approaches to CO_2 separation and capture are needed to reduce cost. Advanced biological and chemical strategies have been identified to address this need. Chemical trapping and concentration can be done with reversible organic processing. Biological processes may be able to use impure and dilute CO_2-containing streams (chemical processes require pure CO_2). Current separation and capture technologies impose significant costs on any process requiring a source of pure CO_2.

Analytical chemistry may provide techniques for monitoring and verifying carbon sources and sinks. Large-scale sequestration will succeed only if we can safely separate, capture, transport, dispose of, or use gigatonne quantities of CO_2, perhaps as part of an international trading regime. The complexity of operating such a system while ensuring human health and safety and protecting the environment will demand extensive monitoring, measurement, and verification capabilities. To keep these costs low, innovative technologies are required that are inexpensive, reliable, easy to deploy and maintain, and capable of measuring quantities of primary interest (i.e., CO_2 leakage rates over a large area, rather than some surrogate measurement).

The other overarching requirement for any of these processes is an accurate understanding of the environmental impacts with respect to products and by-products, their lifetimes, and their dispersal into the environment. One approach to determining impacts is to use a "rough" environmental impact filter for a proposed process, in which upstream and downstream impacts can be assessed from the beginning. For example, what happens to $MgCO_3$ produced via the accelerated carbonation of minerals? Is it reburied, left on the ground, or used in some way?

The Advanced Concepts breakout session included participants with both chemical and biological expertise. The group included about 25 individuals, mostly from government agencies (including national laboratories) but also from industry (BP Amoco) and academia.

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